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COMMUNICATIONS

VISCOSITY MONITORING WITH A QUARTZ CRYSTAL RESONATOR

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The paper describes a novel quartz crystal sensor for measurement of the density-viscosity product of Newtonian liquids. The sensor element consists of two plano-convex AT-cut quartz crystals vibrating in a thickness-shear mode with the liquid sample in between. This special set-up allows suppression of disturbing resonances in the liquid layer. Such resonances are generated in the common single-plate arrangements due to compressional waves caused by spurious out-of-plane displacements of the shear vibrating finite plate. The primary measurands of the sensor are the fundamental resonance frequency and the associated resonance Q-value, which are influenced by the viscously entrained liquid contacting the quartz surface. The sensor was employed successfully in on-line monitoring of waffles dough viscosity.

K e y w o r d s: resonant sensors, viscosity sensor, viscosity monitor, viscosity-density product, dough-viscosity

1 INTRODUCTION

The utilization of thickness-shear mode quartz crystals for the determination of liquid parameters is well known [1–4]. Figure 1 shows a typical arrangement comprising a thin AT-cut quartz disk with electrodes on both sides. One surface of the quartz sensor is in contact with the liquid while the opposite surface is air-backed. The quartz crystal is driven by a high-frequency voltage source V. When operated at a properly chosen frequency (series resonance), the quartz crystal performs in-plane oscillation (thickness-shear mode). This in-plane oscillation radiates a shear wave into the contacting fluid, whereby the decay length of this wave is very small (typically $\approx 1\,\mu$m). The fluid layer contacting the quartz surface causes a resonant frequency shift and a decrease of the resonance Q-value, compared to the unperturbed (dry) crystal. This effect can be utilized to determine the mechanical impedance (real and imaginary parts) of the fluid.

For Newtonian liquids the viscosity-density product can be calculated as [5]

$$\eta_F \rho_F = n^2 \pi Z_Q'^2 \frac{(\delta f_n')^2}{f_{n0}'^3} = \frac{n^2 \pi Z_Q'^2}{4} \frac{1}{Q_{nF}^2 f_{n0}'}\,, \qquad (1)$$

with n: mode number, Z_Q': acoustic impedance (real part) of the quartz, $\delta f_n' = f_{n0}' - f_n'$: frequency shift due to the viscous load of the quartz, f_n', f_{n0}': resonance frequency of the loaded/unloaded resonator, Q_{nF}: acoustic quality factor of the fluid. Figure 2 shows the sensor function of the quartz viscosity sensor calculated from eq. (1) for $f_{10}' = 2.77$ MHz, $f_{30}' = 8.30$ MHz and $Z_Q' = 8.801 \times 10^6\,\mathrm{kgm^{-2}s^{-1}}$.

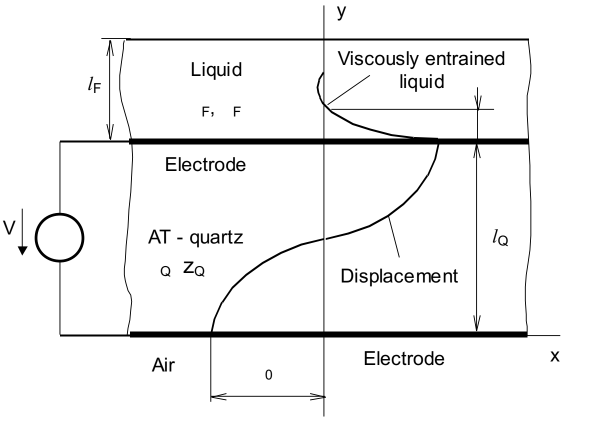

Fig. 1. Displacement of the shear wave in the sensor quartz and in the adjacent fluid layer (schematically).
ρ_F, ρ_Q – mass density of fluid/quartz, η_F – shear viscosity of fluid, Z_Q – acoustic impedance of quartz, l_Q – thickness of quartz layer, l_F – thickness of fluid layer ($l_F \gg \delta$), δ – decay length of shear wave ξ_0 – amplitude at free surface

2 EXPERIMENTAL SET–UP

The utilization of thickness-shear mode quartz crystals for the determination of liquid parameters has shown that, in general, these quartz crystals generate not only a damped shear wave but also compressional waves in the liquid. These compressional waves are caused by spurious

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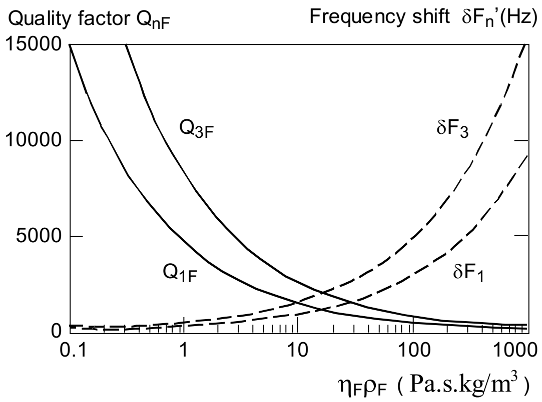

Fig. 2. Sensor function of the quartz crystal viscosity sensor, according to eq. (1), with $f'_{10} = 2.77$ MHz, $f'_{30} = 8.30$ MHz, $Z'_Q = 8.801 \times 10^6\,\mathrm{kgm^{-2}s^{-1}}$, shown for the first and third harmonics.

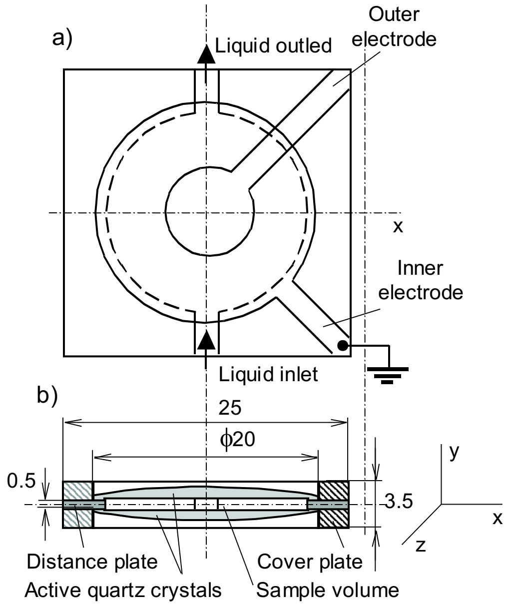

Fig. 3. Sandwich quartz crystal viscosity sensor: a) top view, b) cross section of the resonator.

out-of-plane displacements of the plate surface as a consequence of angular momentum conservation in a shear vibrating finite plate. Since the damping of compressional waves in liquids is much smaller than that of shear waves, (high overtone) compressional wave resonances may occur, affecting sensor performance due to mode coupling and additional energy loss. To overcome this fundamental problem, a special geometry of two quartz crystals with the liquid sample in between has been developed (Fig. 3). The crystallographic orientation of the crystals and the electric potentials are chosen so that the resulting shear displacement curve of the total arrangement is even symmetric with respect to the centre $(x-z)$-plane. The sensor crystals are plano-convex 2.77 MHz AT-cut quartz crystals. The Au-electrodes of both crystals are connected in parallel. The inner electrodes on the plane surfaces are in contact with the liquid and electrically grounded. The cell volume between the active quartz plates containing the liquid sample is equipped with inlet and outlet pipes both of 2 mm inner diameter.

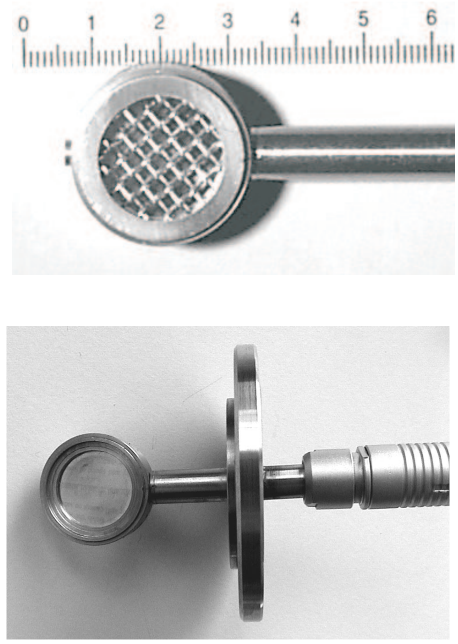

Fig. 4. Photographs of the immersible and the flange type viscosity sensor.

The sensor element is mounted in an aluminium housing and thermostated by a Peltier element in connection with two platinum resistance micro thermometers in the inlet and outlet pipes, respectively. Sample temperature can be controlled accurately within 0.05 °C. Maximum operating temperature of the sensor is 120 °C [6]. For on-line monitoring of viscosity, an immersible sensor has been developed. The quartz crystals are mounted in a stainless steel housing and protected against mechanical damage by means of a mesh. This type of sensor is also available in a flange mounted version that can be inserted, *eg*, into a pipe and operated in flow-through mode with continuous monitoring of fluid viscosity and temperature (Fig. 4). Special electronics were developed to measure the electric admittance spectrum of the crystal. Admittance data were processed by a PC. Viscosity was determined from the resonance Q-value according to eq. (1).

3 RESULTS AND DISCUSSION

The flange mounted sensor according to Fig. 4 was used for on-line monitoring of the viscosity-density product (VDP) of dough during production of waffles (Manner®-Schnitten, Wien, Austria). Figure 5 shows the temporal progress of VDP over a period of several hours. After flushing with clean water (measurements no. 1 and 2)

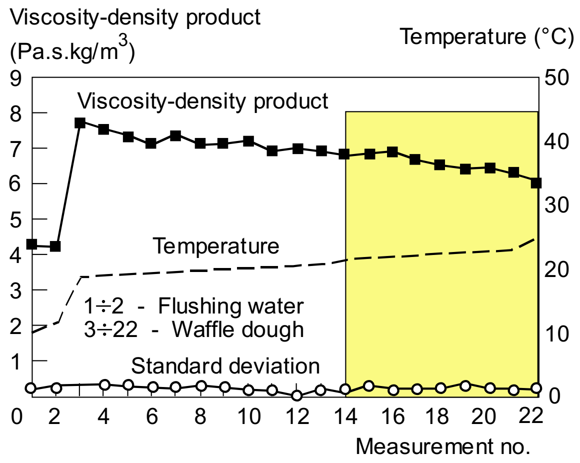

Fig. 5. Temporal progress of dough viscosity-density product (VDP) and temperature measured with the sensor of Fig. 4 over a period of several hours. After flushing with clean water (measurements no. 1 and 2) VDP decreased with time, associated with a respective temperature increase.

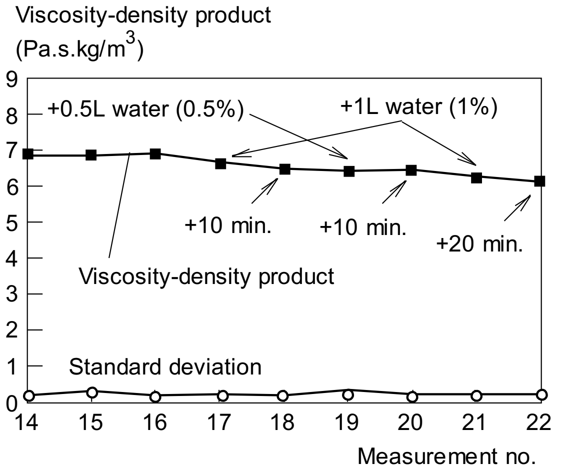

Fig. 6. Part of Fig. 5 (shaded) in expanded scale (measurements no. 14 to 22). By adding small amounts of water (1 vol.% or 0.5 vol.%, respectively), corresponding decreases in VDP could be observed.

VDP decreased with time, associated with a respective temperature increase. Figure 6 shows part of Fig. 5 in expanded scale (measurements no. 14 to 22). By adding small amounts of water (1 vol.% or 0.5 vol.%, respectively), corresponding decreases in VDP could be observed, as indicated in Fig. 6. The introduced quartz crystal viscosity sensor, in combination with a standard density meter, for the first time allows on-line determination of fluid viscosity and therefore is especially suitable for process monitoring applications. Sensor functionality could be demonstrated by measuring the VDP of dough, which is an essential parameter for quality control in waffles production.

Acknowledgements

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Ewald Benes was born in Vienna, Austria, on March 18, 1943. In 1971 he received his MSc degree and in 1976 his PhD in physics at Vienna University of Technology (TUW). His thesis was concerned with the measurement of thin film thickness by use of quartz crystals. Since that time he has been leader of the working group "Sensors and Ultrasonics" at the Institute of General Physics (IAP) of TUW. In 1984 there was his habilitation at the Faculty of Technology and Natural Science of TUW. In 1985 he became associate professor and deputive chairman of IAP. His present scientific activities concern new sensor principles, especially piezoelectric resonators as sensing probes for physical quantities, separation of suspended particles from liquids by ultrasonic resonance fields, and analysis of layered piezoelectric resonator structures. Dr. Benes is member of the Austrian Physical Society and received in 1990 the H. List award of this society for fundamental research with relevance to industrial applications. Since 1993 he has been member of the steering committee of the World Congress on Ultrasonics, WCU, and since 1996 he has been president of the Austrian Acoustics Association. In 1997 he became full professor at IAP. Dr. Benes has published more than 150 papers and holds 12 patents.

Stefan Braun was born in Mödling, Austria, on September 20, 1966. He received his MSc degree in 1992. Subject of his thesis was the investigation of a new method based on quartz crystal sensors for analyzing the visco-elastic behaviour of fluids. After his work in the group of Prof. Benes he did his PhD study dealing with superfluid hydrodynamics at the Institute of Fluid Dynamics and Heat Transfer in Vienna which was finished in 1997. At present, boundary layer separation and laminar/turbulent transition are the fields of his primary interest.

Branka Devcic-Kuhar was born in Bosanska Krupa, Yugoslavia, on April 7, 1956. She received the BSc and MSc degrees in physics from the University of Zagreb, Croatia, in 1982 and 1989, respectively. From 1984 she was employed at Veterinary Faculty, University of Zagreb. She joined the working group "Sensors and Ultrasonics" at the Institute of General Physics, Vienna University of Technology, Austria, in 1993. In 1999 she finished her PhD work that was dedicated to the development of a novel quartz crystal density sensor for liquids. At present Dr Devcic-Kuhar is investigating medical applications of ultrasound, in particular thrombolysis enhancement by high frequency acoustic waves.

Martin Gröschl was born in Vienna, Austria, on September 8, 1959. He received his MSc degree in 1986 and his PhD in physics in 1989 from Vienna University of Technology (TUW). His thesis was dedicated to the development of a novel sensor for beam position control in electron beam evaporation and melting plants. Since 1988 he has been member of the working group "Sensors and Ultrasonics" at the Institute of General Physics, TUW. In 1997 there was his habilitation in the field of technical physics at the faculty of Technology and Natural Science, TUW. His present main research activities are related to the investigation of piezoelectric resonators as sensing probes for physical quantities and to the separation of dispersed particles from liquids by ultrasonic resonance fields. He is especially engaged in the development of electronic equipment for ultrasonic power transducers as well as for measurement systems. Dr. Gröschl has published more than 50 papers and holds 3 patents in the fields of high resolution distance measurement and ultrasonic separation technology, respectively.

Gerhard Karlowatz was born in Mödling, Austria, on October 25th, 1972. He recently finished his master thesis at the Institute of General Physics, TUW, about a computer aided measurement system for acoustical four-terminal properties of probes in a plane-wave-tube. His further research interests include the investigation of piezolectric quartz crystal resonators as sensing probes for fluid properties.

Milan Košťál was born in Bratislava, Czechoslovakia, on April 28, 1946. He received his MSc degree in 1970 and his PhD in 1989 from the Slovak University of Technology (STU). His thesis was dedicated to the field of electronic engineering, namely reverberation time measurement. Since 1971 he has worked at the Faculty of Electrical Engineering and Information Technology, Department of Radioelectronics, STU. His professional activities concern electroacoustics and the evaluation of transmission properties of electroacoustic transducers. He is especially engaged in the development of electronic equipment for various measurement systems. Dr.-Ing. Košťál has published more than 20 papers and holds 10 patents in the fields of electroacoustics and radioelectronics. At present, he is member of the team solving the grant project "Digital Signal Processors and Microcontrollers in Electronics, Radiocommunications and Biomedical Engineering".

Helmut Nowotny was born in Vienna, Austria, on September 26, 1939. He received his MSc degree in 1964 and his PhD in physics in 1970 from Vienna University of Technology (TUW). His thesis was dedicated to the calculation of the temperature dependence of the critical magnetic field of superconductors. In 1977 there was his habilitation in the field of theoretical solid state physics at the faculty of Technology and Natural Science, TUW. Since 1978 he is a permanent member of the working group "Solid State Physics" at the Institute of Theoretical Physics, TUW. His present main research activities are related to the investigation of multi-layer piezoelectric resonators, especially combining analytical and numerical methods of calculation. Other research activities are electronic transport phenomena in rare earth compounds and first-principle calculations for such compounds. Dr. Nowotny has published more than 60 papers.

Rudolf Thalhammer was born in Salzburg, Austria, on October 23, 1964. He received his MSc degree in physics from Vienna University of Technology (TUW) in 1993 and recently he finished his PhD work in the working group "Sensors and Ultrasonics" at the Institute of General Physics, TUW. His work was dedicated to the development of a PC-controlled quartz crystal viscosity sensor for industrial applications.

Felix Trampler was born in Mödling, Austria, in 1968. He received his MSc degree in physics in 1992 for a study on the feasibility of waste water purification by means of ultrasound. In 2000 he completed his PhD thesis about an ultrasonic filtration system for the perfusion of mammalian cell cultures in bioreactors. Dr. Trampler was also engaged in the investigation of the quartz crystal viscosity sensor, especially in sensor electronics development.

(see also back cover)