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# Vibration-induced particle formation during yogurt fermentation — Industrial vibration measurements and development of an experimental setup

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ABSTRACT

The aim of the study was to investigate the effects of vibrations during yogurt fermentation. Machinery such as pumps and switching valves generate vibrations that may disturb the gelation by inducing large particles. Oscillation measurements on an industrial yogurt production line showed that oscillations are transferred from pumps right up to the fermentation tanks. An experimental setup (20 L) was developed to study the effect of vibrations systematically. The fermenters were decoupled with air springs to enable reference fermentations under idle conditions. A vibration exciter was used to stimulate the fermenters. Frequency sweeps (25–1005 Hz, periodic time 10 s) for 20 min from pH 5.4 induced large particles. The number of visible particles was significantly increased from $35 \pm 4$ (reference) to $89 \pm 9$ particles per 100 g yogurt. Rheological parameters of the stirred yogurt samples were not influenced by vibrations.



## 1. Introduction

The texture of yogurt should be creamy, smooth and free of lumps (Sonne, Busch-Stockfisch, Weiss, & Hinrichs, 2014; Tamime & Robinson, 1999). The most common defects of stirred yogurt are syneresis, an insufficient gel firmness, and the presence of large particles, that negatively affect the visual appearance (Lucey, 2004). These particles are protein aggregates and range from 1 to 5 mm (Lucey & Singh, 1997). The composition, like protein content/source and starter culture, influences the formation of these large particles (Remeuf, Mohammed, Sodini, & Tissier, 2003; Küçükçetin, 2008; Küçükçetin, Weidendorfer, & Hinrichs, 2009). Processing parameters, in particular heat treatment of the milk and fermentation temperature, enhance particle formation as well (Küçükçetin, 2008; Küçükçetin et al., 2009). In practice, particle formation is still observed in some batches that cannot be explained according to current knowledge. Certainly, large particles can be removed by shearing, e.g. with back pressure valves or pumping the broken up gel through a mesh (Lucey, 2004). However, excessive shearing leads to structure losses and a decrease in viscosity (Weidendorfer, Bienias, & Hinrichs, 2008). It is well-known that the gelation of yogurt is a mechanically sensitive process. Yogurt production is still carried out batchwise as a continuous production entails several problems (Driessen, Ubbels, & Stadhouders, 1977). Dairy machinery, like pumps, homogenizers (Ismaier & Schlücker, 2009; Kaneko et al., 2014) and switching valves (Berganta, Simpson, & Tijsseling, 2006; Ghidaoui, Zhao, McInnis, & Axworthy, 2005) generate vibrations that are transferred into the fermentation vessels via pipes (Fig. 1) and may disturb the formation of a homogeneous gel structure. There is no research on the effect of vibrations concerning industrial yogurt production. We hypothesize that vibrations negatively affect the gelation and promote the formation of large particles. Nöbel, Ross, Körzendörfer, Hitzmann, and Hinrichs (2016) reported that large particles were induced when ultrasound was applied during lab-scale fermentations. However, it has not been reported yet what kind of vibrations occur in practice. In industrial production, occurring vibrations are random and recipes vary, therefore it is not possible to study the effect of vibrations systematically on an industrial plant. The aim of this study was i) to quantify existing vibrations at an industrial plant and ii) develop and establish an experimental setup for yogurt production that enables fermentations under defined vibrating conditions. Moreover, industrial yogurt samples were taken to get an overview of particle formation in fermented milk products.

## 2. Materials and methods

### 2.1. Oscillation measurements

#### 2.1.1. Measuring system

To get an overview of occurring vibrations in practice, oscillation measurements were performed at an industrial yogurt production

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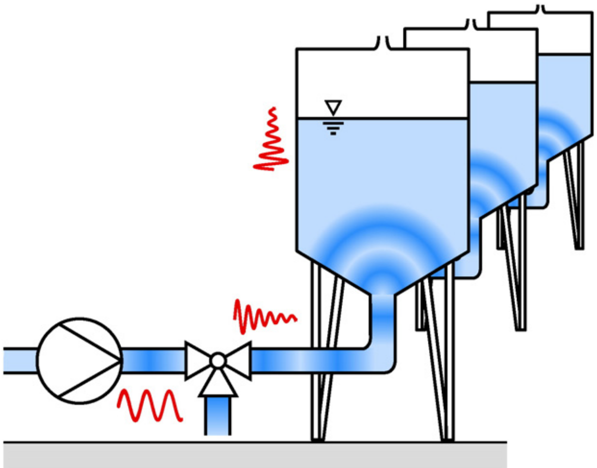

**Fig. 1.** Schematic illustration of an industrial yogurt production line with multiple fermentation tanks. Vibrations generated by pumps or switching valves are transferred into the fermentation vessels and may disturb the gelation by inducing large particles.

line. Accelerometers were attached to the measuring points with a two component adhesive (X60, HBM GmbH, Darmstadt, Germany). The measurements were carried out with piezoelectric accelerometers with internal amplification (8714B, Bruel & Kjær, Bremen, Germany). The obtained signals were digitalized with analog input modules (NI 9237, National Instruments, Munich, Germany) and an A/D converter (NI cDAQ-9174, National Instruments). Processing and storage of data was carried out via LabView2011 (V. 13.0, National Instruments). The data were recorded continuously with a sample rate of 40 kHz and cut to a length of 10 s for further analysis, resulting in a frequency resolution of 0.1 Hz. Recorded time domains were converted to frequency spectra by means of Fast Fourier Transform (FFT) using a FlatTop window function after a band-pass filter (3–10,000 Hz, Butterworth) via DIAdem 2014 (National Instruments). The root mean squares of the vibration acceleration were calculated from the raw signals obtained by the accelerometers. The same measurement technology was used for oscillation measurements on the developed experimental setup (see Section 3.2).

#### 2.1.2. Measuring points

The plant consisted of five fermentation tanks utilizing the same peripherals. Several measuring points were chosen to investigate the propagation of vibrations throughout the plant, focusing on the first tank next to the process machinery. To determine both the source and the effect of the structural excitation, accelerometers were mounted to pumps, valves and the fermentation tanks. One fermentation tank ($V = 40$ m³) was examined more closely as it was nearby the rotary piston pump and the most excessive oscillations were expected there (Kaneko et al., 2014). The production line was monitored for characteristic vibrations throughout the whole fermentation of one batch.

### 2.2. Yogurt production

#### 2.2.1. Standardization and pretreatment of milk

Fresh bovine raw milk was provided from the Location Meiereihof with Kleinhohenheim of the Agricultural Experiment Station (University of Hohenheim). The milk was skimmed at 55 °C (SA 10, Frautech S.r.l., Schio, Italy) and pasteurized (74 °C, 30 s). The protein content was standardized to 3.40 ± 0.01% (w/w) using reconstituted ultrafiltered skim milk permeate, which consisted of 5.2% (w/w) permeate powder (Bayolan PT, BMI e. G., Landshut, Germany) and demineralized water. The milk was heated (95 °C, 256 s) and subsequently cooled to 6 °C by using a pilot plant (150 L/h; Asepto GmbH, Dinkelscherben, Germany).

#### 2.2.2. Starter culture and yogurt fermentation

The fermentation tank including sensors and stirrer was sanitized with steam (>95 °C, 5 min) to inactivate microorganisms and phages. A quantity of 250 g of the frozen starter culture (YC-471, Chr. Hansen, Hørsholm, Denmark) was diluted with 1000 g skim milk (6 °C) to ensure a homogeneous distribution of the two species *Lactobacillus bulgaricus* and *Streptococcus thermophilus*. The stock solution (20% w/w) was thawed at room temperature with occasional stirring. A volume of 50 mL of the starter culture stock solution (0.05%) was added to 20 L milk and fermented at 42.0 °C. The continuous stirring was stopped at pH 6.00, otherwise the gelation would be disturbed. Temperature and pH were monitored continuously. In order to investigate the effect of vibrations during yogurt fermentation, the tank was stimulated with a vibration exciter at pH 5.40 for 20 min. The milk was fermented until pH 4.60.

#### 2.2.3. Stirred yogurt production

After the final fermentation pH was reached, the gel was manually broken by gently moving a perforated disk ten times up and down. A sample was taken from the top and cooled in 1 kg buckets immersed in an iced water bath. After 24 h of storage (6 °C) the yogurt was sheared at approximately 10 °C with a large syringe/piston pump through a nozzle ($d_i = 3$ mm, $l = 25$ mm). The piston was moved by a universal testing machine (5944, Instron, Norwood, USA; software Bluehill 3) to ensure a constant flow rate of 10 mL/s and a calculated wall shear rate of 3800 $s^{-1}$. The whole yogurt production and subsequent shearing were repeated at least five times.

### 2.3. Physical analysis

#### 2.3.1. Transmission images: large particles

Large particles were quantified by means of image analysis (Nöbel et al., 2016). Briefly, a thin layer (1.2 mm) of the yogurt sample was scratched out on a glass plate from which transmission images were taken using a digital camera (8-bit grayscale; MicroPublisher 3.3 RTV, QImaging, Surrey, Canada). The images had a size of 120 × 90 mm (2048 × 1536 pixels) that corresponds to approximately 11–12 g yogurt. Images were automatically analyzed using Matlab 8.3 (R2014a) and Matlab's Image Processing Toolbox 8.2 (The MathWorks Inc., Natick, USA). Data was obtained from at least 15 independent images per sample. Large particles with a diameter ≥ 0.89 mm (15 pixels) were counted and classified according to their size and the median $d_{50,2}$ was calculated.

#### 2.3.2. Rheological measurements: storage modulus and shear stress

Measurements were performed at 10 °C using a stress-controlled rheometer (AR2000ex, TA Instruments, New Castle, USA) with a coaxial cylinder geometry ($d_o = 15$ mm, $d_i = 14$ mm, $l = 42$ mm). Yogurt samples were analyzed 24 h after shearing. Oscillating measurements to determine the storage modulus $G'$ were carried out in the linear-viscoelastic region ($\gamma = 0.0025$) by applying a 30 s time sweep at a constant frequency of 10 rad/s ($G'_{10}$). Afterwards, rotational measurements were done using the same sample. The shear rate was linearly increased from 0 to 500 $s^{-1}$ within 3 min. After a hold step (3 min, 500 $s^{-1}$), the shear rate was linearly decreased to 0 $s^{-1}$ within 3 min. The maximum shear stress ($\tau_{max}$) and the stress at 500 $s^{-1}$ ($\tau_{500}$) at the end of the hold step were calculated. Each measurement was replicated 3 times.

#### 2.3.3. Statistical analysis

R statistic language (V. 3.1.1, R Foundation for Statistical Computing, Vienna, Austria) was used for performing a two-way analysis of variance (ANOVA). A non-parametric Mann–Whitney–Wilcoxon test (U test) was subjoined in case of the effect of sonication. Results are given as arithmetic means and confidence intervals from $t$-distribution ($\alpha = 0.05$). $n$ refers the overall number of examined samples and $i$ to independent repetitions of the experiments.