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Monitoring of single eye growth under known gas pressure: Magnetic resonance imaging measurements and insights into the mechanical behaviour of a semi-hard cheese

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A B S T R A C T

A dedicated setup was developed for simultaneous measurement of pressure and volume in a single eye of semi-hard cheese. A known level of gas pressure was applied to the cheese eye and the resulting eye inflation was monitored using Magnetic Resonance Imaging (MRI). Image analysis methods were developed to measure the eye volume, horizontal and vertical diameters of the eye and the deflected shape of the top surface of the cylinder of cheese under study. Two amounts of pressure were applied to attempt to reproduce a creep-recovery experiment *in situ*. In the last stage, lowering of pressure was applied in order to investigate time-independent elasticity. The core of the semi-hard cheese was found to show no relevant time-independent elasticity during processing in a 90 h experiment. A low amount of pressure (< 3.5 kPa) was able to inflate already existing eyes in semi-hard cheese within the linear domain.

1. Introduction

Understanding cheese mechanics, and the ways it reacts to the formation of an eye, is important in controlling semi-hard cheese processing because it determines whether to focus on gas production, mechanical properties or a mix of both (Huc et al., 2014). Eye growth results from the balance between the increase in amount of gas within the eye and the mechanical resistance the surrounding cheese presents to this increase (Huc et al., 2014; Laridon et al., 2015).

The first step in understanding gas formation in cheese is to monitor the growth of eyes. Advances in imaging techniques make it possible to measure bubble volume or displacements continuously in opaque media. Visualisation of a cluster of eyes in cheese has recently been carried out using X-Ray tomography and MRI in order to evaluate the effects of cheese formulation and processing conditions (Guggisberg et al., 2013; Kraggerud et al., 2009; Musse et al., 2014; Schuetz et al., 2013). Eyes within Gouda cheese of round shape (137 mm in diameter and 69 mm in height) have been observed with an acquisition time of 28 s using X-ray tomography with a slice thickness of 1 mm and a Field of View of 180 mm (Lee et al., 2012). Spatial resolution of 1 mm^3 has been used in parallelepipeds of cheese (dimensions 480 mm × 240 mm × 100 mm) to assess eye distributions accurately with an acquisition time of 51 min (Musse et al., 2014). Other techniques such as ultra-sound also make it possible to assess defaults in cheese (Conde et al., 2008; Eskelinen et al., 2007). However, ultra-sound only reveals the presence of defaults and cannot be used to monitor the growth of a single eye in order to discuss the mechanics in cheese.

The formation of a single bubble and its displacement in a fluid has been studied in boiling water and in molten silica using a high speed camera (Lee et al., 2003; Minami et al., 2011; Mourtada-Bonnefoi and Mader, 2004). The transparent nature of the fluids studied made such monitoring possible using fairly high time frequencies, which are far from the conditions of the growth of a single eye in cheese, for which slow motion is involved in an

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opaque medium.

Since the way a material reacts to a mechanical load (gas pressure) depends on the magnitude and the speed at which the load is applied, simultaneous measurement of both volume and pressure is needed to understand gas expansion. It is necessary to know the volume of the gas bubble to monitor the strain and strain rate within cheese around the gas bubble, and to know the pressure in order to evaluate how much resistance there is to gas inflation. To some extent, the gas pressure inside an eye reflects the stress within the cheese around that eye.

In polymer science, Yano and Shimiya (1988) simultaneously monitored pressure and volume in a single bubble, in order to predict the critical radius at which a bubble shrinks at a constant temperature (Yano and Shimiya, 1988). A droplet of paraffin oil was expanded within a gelatine gel and the pressure was measured using a mercury barometer. The volume was measured photographically, since the medium was transparent. In cheese experiments, known gas pressure was applied in an eye in Emmental cheese using a needle whose base was glued to ensure that the needle remained in place in the cheese. However, eye inflation was evaluated only non-continuously and destructively. The volume of a specific eye was only measured once during ripening. As the eye was cut into halves for volume measurement, the evolution of that eye could not be further measured. Several cheese eyes from different pieces of cheese were used to obtain the volume of an eye over time (Flückiger et al., 1978). No discussion on the connection between gas pressure and the volume of the eye was developed. Expanding a bubble with pressure measurements using an alveograph is a widespread technique that has been used in studying how a bubble behaves during bread making (Codina et al., 2012). However, the growth of an individual eye in cheese under a known gas pressure has been little investigated to date and never with the use of imaging techniques.

In this study, a dedicated setup was developed to maintain a single round eye within a small cylinder of cheese taken from a cheese block during ripening. Special attention was paid to ensure good contact between the cheese and the lateral faces of the setup. The top surface of the cheese cylinder was left free to move. A level of gas pressure was set up at the eye-cheese interface by gas compression inside an injection device. Pressure and volume in the eye were monitored continuously. We present first the methods used to measure eye volume, the horizontal and vertical eye radii and the shape of the deflected upper surface. The expanded standard uncertainties associated with these measurements were estimated. The aim was to investigate the viscoelastic response in a semi-hard cheese to loading conditions similar to those actually found in an eye within a semi-hard cheese block during ripening. Three loading conditions were applied for this purpose, i.e. creep, recovery and lowering of pressure.

2. Materials and methods

2.1. Cheese

A commercial semi-hard cheese block (12 kg, fat/dry 47%, water content 41%, parallelepiped, length 470 mm, width 235 mm, height 90 mm) (Fig. 1) was taken from a production batch at the end of cold room (12 °C for 11 days) at the plant and was sent to the laboratory in a plastic wrap. The cheese block was then ripened in warm room (20 °C for 9 days) in a temperature controlled cabinet (Grand Cru, Liebherr, France).

2.2. Sample preparation

On day 9, a time at which eyes were big enough to be equipped with a needle, a Magnetic Resonance Imager (MRI) (Avanto 1.5 T, Siemens, Germany) was used to locate a single eye inside the block of cheese surrounded by a volume of plain cheese (Fig. 1 a). Once located, the eye (1) (Fig. 1 b) was extracted from the block of cheese within a cylinder of cheese (54.4 ± 0.15 mm in diameter and 32.3 ± 0.15 mm in height) with the help of a stainless steel tube (device not shown). The center of the eye (10.9 ± 0.5 mm in diameter) was set to be as close as possible to the axis of symmetry of the removed cylinder of cheese. The upper surface (3) of the cylinder of cheese was carefully sliced with a steel wire so to make it as flat as possible and also to adjust the distance of the eye from the top surface (3.85 ± 0.85 mm). The cylinder of cheese was placed inside a plastic maintaining apparatus (4) (Fig. 1 b). Before beginning the eye growth experiment the cheese was left for three hours, free of load, in the maintaining apparatus in order to allow any possible remaining stress to relax. The top part (5) of the maintaining apparatus prevented the lateral boundaries of the cylinder of cheese from moving upwards. A cap (6) prevented the top surface of the cheese from drying during the experiment. Pressure equilibrium between the gas chamber (7) above the cheese and the atmospheric pressure was guaranteed by a very small hole (8) in the cap. A needle (9) inserted into the eye on one side and connected to the injection device on the other side (Fig. 1 b) made it possible to increase or decrease air pressure within the eye. This device controls the pressure within the eye. Another cylinder of cheese was extracted from the cheese block symmetrically to the first cylinder (see water content Day 9, Fig. 1 a) in order to check water distribution at the beginning of the experiment to make sure that no heterogeneity of mechanical properties occurred within the cylinders of cheese being analyzed.

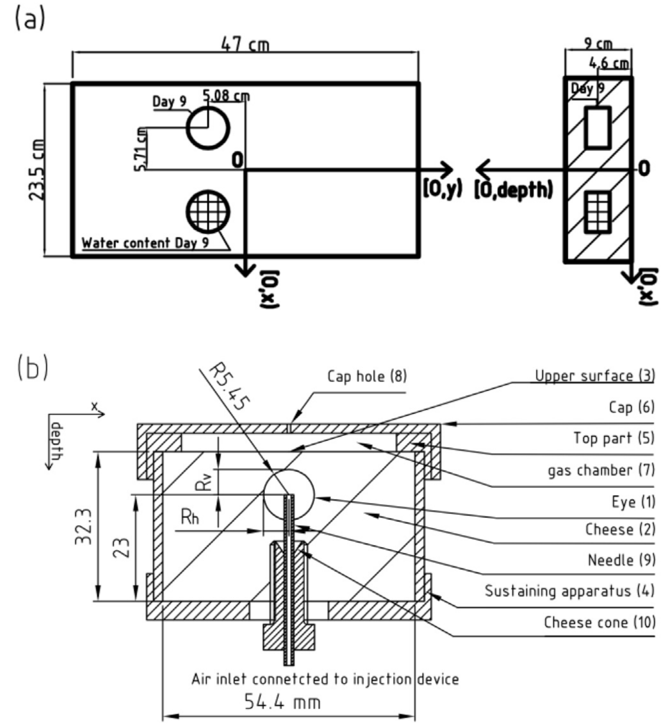

Fig. 1. (a) The cheese block and locations of the cylinders of cheese used for bubble growth experiment and for water content analysis. The 32 small blocks used for the analysis of the water content gradient can be seen in the left- and right-hand side drawings (lattices). (b) Cylinder of cheese in its maintaining apparatus. The height of the cylinder of cheese is in the (O, depth) direction and the width is in the (O, x) direction.