Journal of Food Engineering 185 (2016) 1–8

Contents lists available at ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

Comparison of solid substrates to differentiate the lubrication property of dairy fluids by tribological measurement

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ARTICLE INFO

Article history:
Received 23 December 2015
Received in revised form
27 March 2016
Accepted 29 March 2016
Available online 31 March 2016

Keywords:
Tribology
Surface substrate
Dairy fluid
Surgical tape
Silicone rubber
Ethylene propylene diene monomer rubber

ABSTRACT

Three popular solid substrates (surgical tape, silicone rubber and EPDM rubber) were investigated to examine the lubrication properties of water, aqueous protein solution (3.9% solids), skim (0.1% fat) and full fat (3.8% fat) milk samples with reference with their dry contacts. It was observed that the tribological properties of the test fluids were greatly affected by the physical properties of the solid substrates, particularly wettability. Surgical tape surface, having similar wettability and surface roughness to the surface of the human tongue, appeared to be the best substrate for tribological investigations because of its ability to differentiate dairy solutions with different compositions. Silicone rubber and EPDM rubber, on the other hand, showed the same friction for all the dairy fluids and were thereby not suitable for this tribology test. For very hydrophobic surface like EPDM rubber, the tribological result is governed by the entrapment of air pockets between the solid substrate and the test fluid; therefore, it cannot be explained solely by its physical properties measured in static condition.

1. Introduction

The perception of texture and mouthfeel of food are believed to involve flow and lubrication of food material during the complex oral process including squeezing, rubbing of food between teeth, tongue and palate and their interaction with saliva (Chen and Engelen, 2012; Dresselhuis et al., 2008c; Engelen and de Wijk, 2012). Sensory panels are commonly used to assess food texture, but these are time consuming, expensive and susceptible to a wide range of variations. Therefore, the application of tribology to predict the mouthfeel properties of foods is of growing interest to many food scientists. A tribology device can not only perform screening of a new developed food product but also identify ingredients that provide a desirable mouthfeel sensation, which cannot be detected by bulk rheology (Debon et al., 2010).

In a tribological test, dynamic friction and coefficient of friction between the tribo-geometry and the solid substrate are measured as a function of their relative entrainment speed. Most often an experimental curve, also called a Stribeck curve, is obtained to characterise the behaviour. The Stribeck curve is determined by shearing two surfaces in relative motion over one another at various speeds while simultaneously measuring the friction force from which the lubrication properties of the fluid can be investigated (Dresselhuis, 2008). The Stribeck curve can be generally divided into three different regimes namely the boundary, mixed and hydrodynamic regimes (Prakash et al., 2013). In the boundary regime the separation between the surfaces is smaller than the asperities of the surfaces. Here, the friction coefficient is hardly affected by the sliding speed or the lubricant viscosity but is mainly determined by the chemical constitution of the thin lubricant films covering the solid surfaces. The friction in boundary lubrication is typically 100 times higher than under hydrodynamic conditions but still substantially smaller than for a dry condition because the surfaces are still wetted by molecular layers of the lubricant (Butt et al., 2004b; Williams, 2005). With increasing speed a hydrodynamic film is created that significantly reduces the friction, i.e., the Stribeck curve enters into mixed lubrication. At even higher speeds, the hydrodynamic film is fully developed and completely separates the surfaces. The friction is governed by the internal friction (or viscosity of fluid) and increases linearly with speed (Butt et al., 2004b; Williams, 2005).

Different from the bulk and thin film rheology, the behaviour of the fluid during tribological measurement depends not only on its structure change as the function of entrainment speed but also on

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http://dx.doi.org/10.1016/j.jfoodeng.2016.03.026
0260-8774/

the surface properties of the tribo-geometry and the solid substrate. Consequently, detailed information about the involved surfaces such as structure, roughness, wettability (Butt et al., 2004b; Cassin et al., 2001; Giasson et al., 1997; Ranc et al., 2006a) and visco-elasticity (Butt et al., 2004b; de Vicente et al., 2005; de Vicente et al., 2006) is necessary. Friction also depends on the adhesion between the two sliding surfaces, the presence and characteristics of the lubricant, the interaction between the lubricant and the surfaces and the speed of shearing.

In mechanical engineering, the rubbing surfaces for tribology tests are usually metal, which may resemble the wearing process of a metal mechanical gear. However, in food tribology the surface is often selected such that it resembles oral surface properties. Common solid substrates reported in food tribology tests are metal, rubber, silicone, polymer, etc (Cassin et al., 2001; de Hoog et al., 2006; Krzeminski et al., 2012; Lee et al., 2004; Malone et al., 2003; Ranc et al., 2006b). despite their different characteristics compared to oral surfaces like teeth, tongue and palate. There have been a limited number of studies using a pig tongue surface (de Hoog et al., 2006; Dresselhuis et al., 2008a, 2008b; Ranc et al., 2006a; Ranc et al., 2006b) but this material is difficult for measurement and storage. Since the surface materials commonly used are diverse in structure and physical properties, the obtained tribological results could be completely different when using different surfaces. Therefore, it is important to choose a measurement surface that is suitable for the specific food system being tested.

In this work, we examined some common solid substrates that have been used for tribology measurement to investigate their ability to differentiate dairy fluids of different compositions. The surfaces were surgical tape, silicone rubber and ethylene propylene diene monomer (EPDM) rubber, and the examined solutions were water, whey protein isolate (WPI) solution and pasteurised milk with low (0.1%) and high (3.8%) fat contents. The tribology results of the solutions in comparison with dry contact will be investigated for all the surfaces in relation with three important surface properties: wettability between the fluid and the surface, the elastic modulus or stiffness of the solid substrate and the surface roughness.

2. Materials and methods

2.1. Materials

In this work, we investigated the interaction between four solutions and three solid substrates. The four solutions were water, WPI solution (3.9% w/w) reconstituted from WPI powder (Fonterra, Australia) and two commercial pasteurised milk samples – skim milk (3.9% w/w protein and 0.1% w/w fat) and full fat milk (3.6% protein w/w and 3.8%fat w/w). The three surface substrates used were surgical tape (Transpore Surgical Tape (3M Health Care, USA)), silicone rubber and EPDM (ethylene propylene diene monomer) rubber (NDA Engineering Equipment Ltd., England).

2.2. Contact angle measurement

The contact angles between the solutions and solid surfaces were measured using sessile droplet method by contact angle measuring instrument OCA 20 (Dataphysics, Germany) with a droplet volume of 10 μL at ambient temperature.

To examine whether or not a solution adsorbs onto a solid surface and affects the wettability and tribology result, we deposited a big droplet of that solution to cover a large area on the surface and let it equilibrate for 15 min. The solution was then gently washed off with running distilled water and dried naturally at room temperature for 30 min. The water contract angle was remeasured by the same procedure as above. Any difference between measured angles before and after the surface had come into contact with the food solution was an indication of fat or/and protein adsorption onto the surface (Giasson et al., 1997).

2.3. Surface stiffness measurement

Apparent stiffness of the solid substrate was measured by puncture test using a Texture Analyser (TA-XT*plus*; Stable Micro Systems Co., UK). The probe was a stainless steel needle. The solid substrate was fixed to a sample holder with a groove of 5 mm width. The puncture test was performed in a compression mode with a test speed of 0.5 mm/s. The apparent stiffness modulus (N/mm) of the solid substrate was determined as the slope of the force-distance curve (Tuyen et al., 2009).

2.4. Surface roughness analysis

Surface topology and roughness of each solid substrate were measured using a DEKTAK 150 Profilometer (Veeco, Inc., USA) with 12.5 μm radius stylus at 3 mg contact force.

2.5. Rheological measurement

Viscosities of water, WPI solution and milk samples were measured by steady state shear rheometry, using a shear rate-controlled rheometer (Discovery Hybrid Rheometer, TA Instrument, USA) using 60 mm stainless steel parallel plates at 100 μm gap, with shear rate ranging from 0.1 to 1000 s^{-1}. A solvent trap cover and a standard Peltier plate with solvent trap filled with deionized water were used to mitigate sample drying during the experiment. The sample was equilibrated at room temperature (22–25 °C) for 1 h before measurement. At the beginning of each test, the sample was equilibrated again for 60 s at 35 °C between the parallel plates at the measurement gap. All testing was conducted in triplicate at 35 °C.

2.6. Tribological measurement

Tribological measurements were performed on a Discovery Hybrid Rheometer, using half-ring on plate tribo-rheometry (TA Instrument, USA) on three different solid substrates: surgical tape, silicone rubber and EPDM rubber. This tribometer configuration has been presented elsewhere (Nguyen et al., 2016).

The solid substrate was cut in a square shape, placed and fixed on top of the lower plate geometry before the measurement. While the surgical tape can be secured directly on the lower plate, the other two substrates were fixed on the lower plate using double-sided tape. After each measurement, the substrate was replaced and the tribo-rheometry was cleaned and dried with deionized water and laboratory wipes. For silicone rubber and EPDM rubber, if there was no visible wear or defect observed, the substrate was reused after being washed and dried thoroughly.

The sample was equilibrated at room temperature (22–25 °C) for 1 h before measurement. The tribology measurements were performed at 35 °C to simulate the oral processing condition. Since the in-mouth force was reported to be between 0.01 and 10 N (Miller and Watkin, 1996), we maintained the normal forces of 2 N during the measurement to represent the moderate normal force applied on dairy foods during oral processing. The results were recorded for rotational speeds from 0.01 to 100 s^{-1} with 20 points per decade. All tests were conducted in triplicate.