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Importance of tribology in food and dairy industries: An overview

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Abstract
Tribology is an emerging discipline in food technology. Tribology is the science related to friction, lubrication and wear. The tribological characteristics of food provide information about the frictional interactions of food with the surfaces of the tongue, palate and teeth. Mouth feel attributes such as creaminess, smoothness, slipperiness, astringency are all related to tribology. Due to this obvious implication of food tribology it has attracted growing interest in food industries to develop tasty fat-reduced food to combat increased number of fat related diseases worldwide. In food tribology, the lubrication behavior of food samples can be understood with a well-known Stribeck curve that is a plot of the coefficient of friction against a combined parameter of viscosity, speed and load. Commercially available instruments that can mimic fat related sensory attributes are friction meter, optical tribological configuration, mounted tribological device, tribology cell, and mini-traction machine.

Keywords: Tribology, food texture, mouth feel, food rheology and creaminess

Introduction
Eating is a dynamic process and so is a sensory perception. During eating, an individual sensory feature changes its intensity and accordingly there will be a changing profile of the dominating sensory feature. This dynamic process is directly linked to or caused by the changing length-scale of food particles and the length scale involved in the deformation process that controls a materials mechanical response. The textural features sensed at early stages of oral processing are those mostly dominated by bulk phase properties whereas those sensed at a later stage of oral processing are related to a thin film of product and/or product-saliva combination that affects oral surface properties and oral lubrication (Engelen and De Wijk, 2012) [11]. For this reason, tribology is emerging as a new discipline for food texture studies, where lubricating properties of food are measured by using equipment that operates on the same principle used in mechanical engineering for determining the frictional properties of lubricants.

Tribology is the study of friction, wear and lubrication of interacting surfaces which are in relative motion. It is also known as thin layer rheology. Tribology provides an important approach to determine properties of materials in the form of thin film that cannot be deduced from bulk properties (Baier *et al*., 2009) [1]. From food sensory perspective, tribology can be understood as the frictional and other related physical properties exhibited by food when squeezed and sheared between the two moving surfaces (i.e. the tongue and the palate) during oral processing (Dresselhuis, 2008a) [8].

The main parameter for a tribology test is the friction coefficient, calculated as the ratio of the measured friction force against the normal load. The friction coefficient is a constant dependent only on the properties of the contacting surfaces when they are in dry movement, but could vary significantly according to surface load and fluid viscosity when a thin layer of fluid is trapped between the two surfaces (Bongaerts *et al.*, 2007) [2]. Sensory attributes such as creaminess, smoothness, slipperiness, astringency, roughness can be described through tribological data.

Pioneering work of food tribology research was conducted quite a while back by Kokini *et al.* (1984) [21], Kadane *et al.* (1977) [20]. They applied tribology approach to investigate the dominating physical nature of sensory smoothness, slipperiness, creaminess and other textural features of fluid and semi-solid foods. The tongue and palate interaction was very appropriately illustrated as a lubrication system, commonly known as Kokini model, where the tongue moves against the surface of hard palate where the fluid food (mixed with saliva) is sheared or functions as a lubricant for the moving surfaces. Surprisingly, Kokini’s work wasn’t picked up by many food researchers and was echoed only fairly recently by De Wijk *et al.*

(2003) [7] who showed that the quality and also the thickness of oral coating are of great importance for the perception of the creaminess of custard products. The existence of a thin layer of food residue on oral surfaces has been experimentally confirmed. By using confocal endoscopy technique, Adams *et al.* (2007) observed *in vivo* a thin layer of oil (or oil droplets) at the tongue surface even 30 sec after oral processing.

Since the advent of tribology, there has not been much progress from food perspective, due to both the lack of appropriate technique for food studies and the lack of fundamental understanding of its relevance to food oral sensation. This led to huge efforts among food scientists in seeking appropriate experimental techniques to conduct reliable food tribology and lubrication studies. In doing so, a unique challenge faced by food scientist is the very complicated tribological scenario inside human mouth, the typical oral physiological factors as well as the food factors. The factors influencing food oral lubricity are broadly classified into food system and oral system.

Difference between rheology and tribology

During eating, an individual sensory feature changes its intensity and accordingly there will be a changing profile of the dominating sensory feature. This dynamic process is directly linked to or caused by the changing length-scale of food particles and the length scale involved in the deformation process that controls a materials mechanical response. It is hypothesised that textural features sensed at early stages of oral processing are those mostly dominated by bulk phase (rheology) properties whereas those sensed at a later stage of oral processing (tribology) are related to a thin film of product and/or product-saliva combination that affects oral surface properties and oral lubrication.

Food rheology approach was first developed almost half a century ago and has been proved to be a useful technique for food texture studies. The principal assumptions of this approach are that an eating process is a destructive process involving deformation, flow, fracturing and breaking of the food, and that texture is brain interpretation of the oral sensation of material's responses and resistances against such deformations. Based on these assumptions, the sensory perception of food texture is wholly physical-originated and is determined almost solely by the mechanical properties of the food material (Fisher & Windhad, 2011).

Tribological behaviour of a material is critical in almost all engineering and machinery designs. The main parameter for a tribology test is the friction coefficient, calculated as the ratio of the measured friction force against the normal load. The friction coefficient is a constant dependent only on the properties of the contacting surfaces when they are in dry movement, but could vary significantly according to surface load and fluid viscosity when a thin layer of fluid is trapped between the two surfaces (Bongaerts *et al*., 2007) [2].

Principle

The friction behaviour of lubricants is often represented in form of a so-called Stribeck curve, where the friction coefficient is plotted as a function of film thickness or as a function of a so-called friction parameter (defined as speed x viscosity/load) as shown in Fig. 1. The combination of three parameters gives a unit of length (m), resembling the thickness of the lubricant film between the two moving surfaces. A Stribeck curve can be typically divided into three regimes-the boundary regime, the mixed regime, and the hydrodynamic regime, representing three very different friction scenarios and, in case of oral processing, different amount of food sample between the tongue and palate.

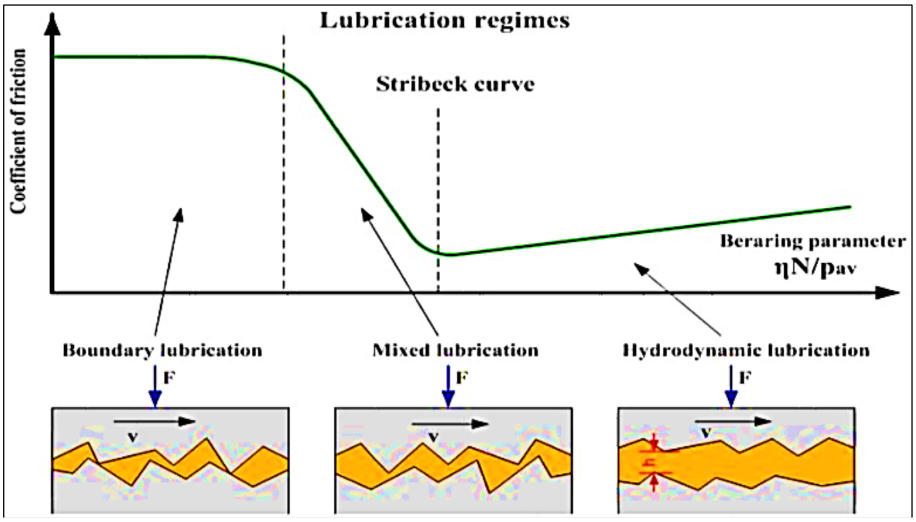

Fig 1: Stribeck curve

a) Hydrodynamic regime

When food is consumed then initially the rate of entrainment of the food into the contact zone due to surface motion results in a sufficiently high fluid pressure to fully separate the surfaces and this process is called hydrodynamic lubrication. Two surfaces in relative motion are in complete separation by a thin layer of fluid, a hydrodynamic lubrication regime is defined. In this case, there is no surface wear and surface friction increases due to fluid drag force.

b) Boundary regime

If the hydrodynamic fluid pressure is insufficient to separate the palate and tongue, then the lubrication properties of the food depend on the ability of the food's constituents to form boundary films. Boundary layer lubrication occurs when surfaces are in close contact, where their asperities or roughness could cause the surfaces to lock up and result in severe surface wear and a high friction coefficient. This might be the regime closely related to human perception of astringency, slipperiness.

c) Mixed regime

Between the boundary and the hydrodynamic regime lies the mixed regime of lubrication. In this regime, the food entrainment into the tongue–palate contact zone is sufficient to partly separate the two rubbing surfaces. However, the lubricant film thickness and the height of the asperities of the substrate surfaces are of similar dimensions, so the contact load is borne in part by fluid pressure and in part by asperity contact pressure. The friction coefficient reaches a minimum in this regime and, with either increased asperity contact or increased thickness of the lubricant layer, the friction coefficient will increase.

Recent progress of tribology in food

Chojnicka-Paszun *et al.* (2012) [6] related sensory perception of homogenized milk (fat content between 0.06 and 8%) with friction coefficient and viscosity. At fat content above 1% they observed a linear correlation between perceived creaminess and friction coefficient. The increased creaminess and thus decreased friction were attributed to the coalescence of fat globules on the surface of the tongue and rubber disc.

Paszun *et al.* (2012) [6] conducted an experiment to correlate homogenized milk with a fat content between 0.06 and 8% with its friction coefficient and viscosity. They observed that above a threshold of 1% fat, there was a strong decrease in friction coefficient at low speeds, which is associated with shear-induced coalescence. Creamy perception was perceived only for products with the friction coefficient below 0.25 for silicone rubber at entrainment speeds lower than 200 mm/s. Under those conditions, a linear correlation between perceived creaminess and friction was obtained at a fat content above 1%. The increased creaminess and thus decreased friction was attributed to the coalescence of fat globules on the surface of the tongue and rubber disc, respectively. At higher speeds, fused fat droplets were broken into smaller droplets (reversing coalescence) due to the high shear, thereby eliminating the correlation.

Selwaey and Stokes (2013) formulated commercial soft-food systems-custards, yogurts and thickened creams at varying fat levels with the aim of maintaining consumer acceptability using rheology and soft tribology to gain insight into the physical origins of mouthfeel and the dynamics of oral lubrication, including the role of saliva. They demonstrated the use of tribology to differentiate soft-food systems that exhibit similar rheological behavior, based on their transient lubrication properties.

Nguyen (2016) used a simple method to measure lubricating properties (friction coefficient) of dairy products is presented using a newly introduced tribometer coupled with a widely used rheometer. Pasteurized milks (fat contents from 0.1% to 4.9%) and cream cheeses (fats content: 0.5%, 5.5%, 11.6%) were chosen as representative dairy products and their friction coefficients were measured as a function of entrainment speed of the tribometer. The friction coefficients of the samples at low entrainment speed generating low shear rate (similar to the shear rate in mouth) were significantly different between the samples at each fat levels. They suggested that this method was capable of differentiating samples with different fat contents both in liquid or semi-solid forms.

Liu *et al.* (2016) investigated the tribological properties as well as rheological properties of native and gelatinized rice starch in liquid o/w emulsions and semi-solid emulsion-filled gelatin gels and observed that the presence of oil droplets in rice starch- o/w emulsions could reduce the friction caused by stickiness of gelatinized rice starch. From the study they conclude that morphology and surface properties of the starch particles, bulk and breakdown properties of matrices are the main factors that determine the tribological profile of food model systems.

Zhang *et al.* (2017) studied first time the lubrication and rheology of aqueous suspensions of isolated swollen starch granule ghosts over a wide range of concentrations, using maize and potato starches as exemplars and concluded that conclude that soft-tribological properties of starch ghost suspensions can be due to either particulate (e.g. maize ghosts) or polymeric (particularly for potato ghosts) forms, the balance between which could potentially contribute to the perception of starch-containing food in the mouth and properties of starches as processed and used in a wide range of application.

Instruments used to study tribological property

Friction can be measured using a tribometer. Several types of tribometers are developed and used in the area of food research. The differences among these tribometers are often regarding the type and speed of the surface movements, contact area between the surfaces, and the surface materials. These parameters can be modified and adjusted to mimic the environment of the human mouth. In most food studies measuring tribological parameters, either a commercially available tribometer system or a custom-made system is utilized.

The two most critical factors taken into account in the design of a tribometer to mimic oral processing involves

1. The control of the sliding and or rotating between the two surfaces.
2. The surface properties of the substrate materials.

Different tribometers with advantages and disadvantages is listed below in table 1.

Table 1: List of tribometer used in food studies

Instruments	Principle	Advantage	Disadvantage
Friction tester	Spherical ball rotating against rubber band Developed in-house	Simple and easy to use	Lack of well controlled temperature
Optical tribological configuration	Detachable surface applying force against oscillating glass surface Developed in-house	Study microstructural changes of sample	Restricted load and speed applied
Mounted tribological device	Ball rotating on three motile plates	Runs at higher load and sliding speed	Inaccuracy in Friction coefficient measurement
Tribology cell	Two cylindrical contact points rotating against annular disk Developed in-house	Inexpensive and convenient	Required validation of the capability for non-Newtonian Fluids
Mini-traction machine	Spinning disk against rotating ball	Accurate and sensitive	Expensive

*Recently, mini-traction machine (MTM) is mostly used to study the tribological measurements.

Applications

The study of thin layer properties of food materials in tribology has increased the attraction of the researchers and food industries toward various applications. Some of the applications of food tribology are listed below in the given points:

a) Development of a tasty fat-reduced food product with consumer's acceptability.
b) To differentiate dairy product according to different level of fat content.
c) In beverages industries it is applied to know the astringency of product.
d) To study swelling characteristics in starch.

Table 2: Product details

Products	Parameters studied	Application	References
Gum and carboxymethyl cellulose, honey, butterscotch syrup, pancake syrup, vanilla syrup and chocolate syrup	Smoothness and slipperiness	Fat affects fat-related sensory attributes include lubrication (friction) and flavor release.	Kokini *et al.* (1977)
White sauce (0-24.8% fat), vanilla custard (0.5-3.6% of fat) and mayonnaise (16-72% of fat)	Creamy and fatty mouth feel and fatty after-feel	Lowest for starch-based custards after enzymatic break-down of the starch by salivary amylase	De Wijk and Prinz (2007)
Whole milk, skim milk, cream, cream topping, and cool whip, butter, whipped butter, and cream cheese, ice creams, ice milk, sherbet, and frozen orange juice	Smoothness	-	Kokini and Cussler (1983)
Corn syrup with demineralised water.	Thin film sliding and shearing	Breakdown behaviour of food hydrocolloids and emulsions	Goh *et al.* (2010) [14]
Tea catechins Skimmed milk fortified with inulin Milk with 0.06-8% fat	Astringency	Depletion of the lubricating proteins from the elastic substrates.	Rossetti *et al.* (2009) [27]
Vanilla custard varying in fat, starch and variety of starch. Vanilla custard with different particle sizes of silica dioxide, mayonnaise	Roughness, creaminess and astringency	Alpha-amylase, an enzyme present in saliva that initiates the digestion of starch, plays a role in the initial breakdown of food and may cause a drop in perceived thickness of the food	Dewijk and Prinz (2005)
Emulsions prepared from whey protein isolate and sunflower oil	Roughness, fatty mouth feel	Modification of smooth modified poly dimethyl siloxane in food	Dresselhuis, De Hoog, Cohen Stuart, Vingerhoeds, and van Aken (2008) [9]

Advantages

Application of tribology to study food behaviour cannot be neglected because of its following advantages:

1. It encompasses both the fluid's rheological properties as well as the surface properties of the interacting substrates.
2. It explains the thin layer behavior of food where rheology is failed to explain.
3. It defines the complete sensory or mouth feel perception of food product.
4. It studys the lubricating properties of food materials such as slipperiness, creaminess, smoothness, astringency.
5. There is no risk of hazard.

Limitations

1. It cannot be applied for solid or particulate food materials.
2. Further processing (heating or microwaving prior to consumption) of engineered foods may change the tribological characteristics of texture-defining molecules and, thus, alter the sensory properties of the food.
3. The equipments used to measure tribological measurements are expensive.

Future suggestions

- Development of tasty fat reduced food product since it study creaminess, smoothness.
- In dairy products it can be applied to differentiate to samples of different fat content.
- Prediction of sensory mouthfeel related to lubrication properties for beverage and semi-solid food products.
- Need to interpret transient lubrication measurements in the context of oral processing.

Conclusions

Tribological studies on food systems in the past few decades have been inadequate due to the limitation of technology. However with the recent emergence of new experimental devices there has been a surge in research and development in food tribology area. Data obtained from various tribology devices show that friction and lubrications properties of food samples can be measured and related to attributes like fatty feel, astringency, smoothness, roughness, and slipperiness. Few most representative tribology apparatuses have been discussed in this paper, from the former technology, such as friction tester, to the latest technology, mini-traction machine. It is stressed that, besides applying an appropriate sliding speed and load for accurate tribological measurements, another important factor that should be considered is the representative surface on which the measurements are conducted. It has been demonstrated that different surface characteristics lead to completely different lubricating behaviour of the same food. PDMS is currently a feasible choice for food tribology studies due to its elastic characteristics close to that of tongue tissue. Although very limited studies is available on application of tribometer in food systems, the outcomes so far show great potential of the approach in establishing relationship between tribology parameters and the perceived texture and mouth feel attributes.

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