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Movement of a secondary immiscible liquid in a suspension using a non-invasive technique

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ABSTRACT

In this paper, the movement of a secondary immiscible liquid when added to a suspension of hydrophilic particles in a continuous hydrophobic phase is investigated. This was achieved through an approach using high speed camera and X-ray computer tomography. These non-invasive approaches allowed the secondary liquid displacement within the suspension to be monitored on the surface level and within the suspension through a time lapse of scans.

The addition of a small amount of secondary liquid to suspensions, can lead to a transition from a fluid-like to paste-like structure. The kinetics taking place and responsible for this, during both short and long term storage were investigated to better understand the mechanisms taking place. Water was added as the secondary immiscible liquid to suspensions composed of sucrose (icing sugar) and sunflower oil. Different volumes of secondary liquid were added to the suspensions. The rate of movement as well as the spreading of the secondary liquid into the suspension was calculated from the scans taken. The surface area to volume ratio was proposed as a reason for the spreading of the liquid for the smaller volume droplet being greater in comparison to the larger volume droplet.

1. Introduction

Many food products are composed of suspensions in which a solid phase (hydrophilic particles) is dispersed throughout a continuous liquid phase (hydrophobic liquid). An example of this is peanut butter spread. When small amount of a secondary immiscible liquid such as water is added to suspensions, the change from a fluid like material to a paste like material can be seen (Koos and Willenbacher, 2011). This change has been attributed to the formation of liquid bridges, between the secondary liquid and the primary particles which in turn alters the rheological properties of the suspension (Negreiros et al., 2015). The secondary liquid has a greater affinity to the primary particles in comparison to the continuous phase, due to their hydrophilic nature. The adhesive forces between the particles and secondary liquid are sufficient to allow the structure to maintain its shape, once a paste like material is formed. As well as the visual effects of adding small amounts of secondary liquids to suspensions, it has been shown that the rheological properties such as the yield stress and viscosity can increase several folds (Koos and Willenbacher, 2012). Also, this can lead to faster sedimentation, as with the addition of water, aggregates will form which settle due to gravitational effects (Yucel and Coupland, 2011).

Exposure of suspensions to high humidity environments, can also lead to major characteristic changes. This is of extreme importance to behaviour during manufacturing and processing of suspension based food produce in high humid environments, as this will ultimately affect the properties and shelf life of the end product. This is of particular importance,

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Nomenclature

LIST OF SYMBOLS

d_{32}	Diameter of a sphere with same volume/surface area ratio [m]
P_c	Laplace capillary suction pressure [Pa]
r_d	Contact radius of droplet with powder bed [m]
R_{pors}	Characteristic size of bed [m]
V_0	Drop volume [m^3]
t'	Volume of liquid penetrated at time t [s]
φ	Sphericity of the particles [dimensionless]
ε	Porosity [dimensionless]
μ	Viscosity of liquid [Pa s]
γ_{LG}	Interfacial tension between liquid and gas [N/M]
θ	Contact angle [°]
τ_{CDA}	Penetration time for constant drawing area case [s]
τ_{DDA}	Penetration time for decreasing drawing area case [s]

as from this phenomenon of moisture movement, microbial growth and chemical reactions within food products may occur, and thus lead to substantial food wastage (Ghosh et al., 2004). By understanding the kinetics occurring, this may allow for tailored food products which will help reduce wastage in the long term.

The addition of liquid to dry powder beds, for different compositions of hydrophilic and hydrophobic powder mixtures was studied by Nguyen, Shen (Nguyen et al., 2009) looking at the penetration time and shape of the droplets formed. It was shown that the material properties of the powder in terms of its hydrophilic/hydrophobic affinity greatly influence the penetration rate and granule formation.

For a suspension the movement of moisture can be from the environment or between the different domains within the suspension (such as the multi-domain food product, with a filling and outer coating e.g., wafer ice-cream), and will take place provided there is a concentration gradient between the two in question. The recent work in the literature has been based on the assumption of diffusion being the dominant mechanism and basing models on apparent/effective diffusivities to simplify the mechanisms (Yuan et al., 2009, 2012). However, it is understood that it is more probable that a combination of transport mechanisms are taking place such as gravity, capillary and diffusion (Ghosh et al., 2004).

From the qualitative studies mentioned, it is difficult to follow the localised mass transfer of moisture. These studies only quantify and analyse the bulk mass transfers as an overall average of the sample and do not determine the kinetics of movement taking place locally. A non-invasive approach would allow for the mass transfer to be seen qualitatively thorough a sequence of images. These images can then be analysed in a quantitative manner.

Currently, there is no work which has been able to track and quantify the localised mass transfer of a secondary immiscible liquid within a suspension. The present work uses a novel non-invasive method of X-ray computer tomography to monitor the movement of a secondary liquid within a suspension, through a sequence of scans, taken at different time intervals. Through this new approach, it was possible to study the movement of a secondary liquid with time within a suspension. Thereby, allowing the kinetics to be quantified and better understood.

2. Materials and methods

2.1. Materials

Suspensions of sucrose (icing sugar, ZMR Zuckermühle Rupperswil AG, Germany) and high oleic sunflower oil (Surface tension 35.5 mN/m, FTA125. Viscosity 49 m Pa s, Malvern Kinexus lab+. Measured at 25 °C) were prepared by mixing using an overhead mixer (IKA, RW16) with a marine impeller (A100, Lightnin UK) at 650 rpm for 10 min. The mass fractions of the solid and continuous phase were 50 wt%. This was chosen so as to minimize the effect of settling of solid particles, while ensuring sufficient presence of the continuous phase to coat all the solid particles. The solid particles had a size distribution of 9–110 μm, with a d_{50} of 32 μm. This was measured by laser diffraction using Malvern Mastersizer S (Malvern Instruments, UK).

Suspensions once prepared were transferred into cellulose straws (9 mm diameter, Fishers Ideas UK) attached to a brass chuck designed for the X-ray μCT using a disposable pipette. A specially prepared lid with a hole in the centre to fit the pipette tip was then placed on top, to ensure the addition of the secondary liquid was to the centre of the sample. The secondary liquid, which was distilled water, was added to the surface of the suspension using an electronic pipette (Eppendorf Xplorer, UK), positioning the tip of the pipette close to the surface of the suspension but without actually touching the surface. The distance between the tip of the pipette and the surface of the suspension was approximately 5 mm. Once the secondary liquid was added, para-film was used to cover the hole to prevent the evaporation of the secondary liquid.

2.2. High speed camera

Tablets of sucrose were produced using the Instron testing machine (Instron 3367, USA). The compression force used was 6250 N, for a mass of 5 g in a 30 mm diameter die. Water penetration tests were conducted on these tablets with and without oil to see the initial capillary suction. High speed camera (Photron, 100KC) images were taken with a 1000 frame rate per second, to capture the droplet penetration into the tablet. A fixed volume of water (dyed with erythrosine B, for ease of identification) was deposited onto the surface of the tablet and the penetration of the droplet was recorded. The experimental set-up can be seen in Fig. 1.

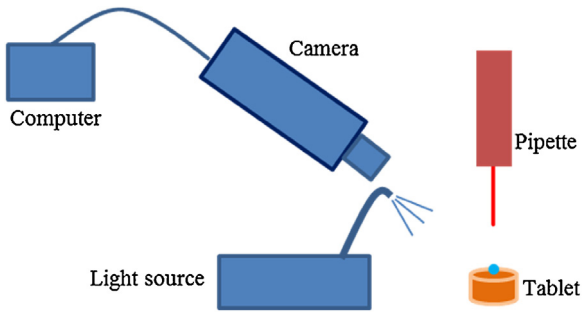

Fig. 1 – Schematic of setup for penetration tests.

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