CHARACTERISATION OF POTATO CRISP EFFECTIVE POROSITY USING MICRO-CT

Ryan C. Renshaw[a,b*], John P. Robinson[b], Georgios A. Dimitrakis[b], John R. Bows[c], Samuel W. Kingman[b]

[a] e2v technologies (uk ltd), 106 Waterhouse Lane, Chelmsford, Essex, UK, CM1 2QU

[b] Energy and sustainability research division, Faculty of engineering, University of Nottingham, University park, Nottingham, UK, NG7 2RD

[c] PepsiCo Europe R&D, Beaumont park, 4 Leycroft Road, Leicester, Leicestershire, UK, LE4 1ET

[*] Corresponding author. Tel. +44 1245 493 493

E-mail address: ryan.renshaw@googlemail.com

Keywords: Micro-CT, porosity, potato, microwave, frying

ABSTRACT

BACKGROUND:

The effective porosity is an important quantitative parameter for food products that has a significant effect on taste and quality. It is challenging to quantify the apparent porosity of fried potato crisps as they have a thin irregularly shaped cross section containing oil and water. This study uses a novel Micro-CT technique to determine the solid volume fraction and hence the effective porosity of three types of potato crisps – standard continuously fried crisps, microwaved crisps, and continuously fried “kettle” crisps.

RESULTS:

It was found that continuously fried kettle crisps had the lowest effective porosity at 0.54, providing the desired crunchy taste and lower oil contents. Crisps produced using a microwave process designed to mimic the dehydration process of standard continuous fried crisps had an effective porosity of 0.65, which was very similar to the effective porosity of 0.63 for standard continuously fried crisps. The results were supported by the findings of a forced preference consumer test.

CONCLUSION:

The effective porosity affects the product taste and is therefore a critical parameter. This study shows that Micro-CT analysis can be used to characterise the change in effective porosity of a thin irregularly shaped food product, caused by a change of cooking procedure.

NOMENCLATURE

f	Mass fraction [kg.kg^{-1}]
m	Mass [kg]
v	Specific volume [dimensionless]
V	Volume [m^3]

Greek symbols

ρ	Density [kgm^{-3}]
ϕ	Porosity [dimensionless]
ϕ_{eff}	Effective porosity [dimensionless]

Subscript

g	air
o	oil
t	true
T	Total or apparent
s	solid
w	water

INTRODUCTION

Fried potato crisps are a porous, irregularly shaped heterogeneous medium. The volume fractions of solids, oil and moisture are vital parameters for potato crisps. These parameters control the density and porosity of the product as well the taste, shelf life, and fat content. Porosity in particular is an important quantitative parameter that has a significant effect on mechanical, textural, and quality characteristics of dried material. (1) There has been a recent drive to optimise these parameters with particular focus on oil content and taste/texture due to demand for healthier snacks. Typically, crisps are fried using either a continuous fryer (regular crisps), or a batch fryer ("kettle" crisps). In the continuous method, sliced and washed potatoes are continuously introduced into a vat of frying oil at a temperature of about 185^{o}C or higher. They are conveyed through the oil by paddles or other means, and removed from the oil about two and a half to three minutes of frying by a conveyor belt when the moisture content of the crisps has been reduced to about 0.02 kg kg^{-1} by weight or less. (2) It is important that the final moisture content is less than 0.02 kg kg^{-1} to obtain a low water activity, and hence an acceptable shelf life. The crispness of the product is also dependant on an extremely low final moisture content. (3) The resulting product generally has texture and flavour characteristics which are usually recognisable by consumers as typical commercially produced continuous process potato crisps. Potato crisps produced by batch processes in kettle fryers are generally harder and crunchier than continuously fried crisps and have a flavour that some consumers find more appealing than typical continuously fried commercial crisps. As the name implies, batch process kettle frying of potato crisps involves placing a batch of unwashed potato slices in a kettle of hot oil, at an initial temperature of about $150^{o}C$. The cooking oil temperature follows a generally U-shaped time versus temperature profile where the temperature of the oil typically drops quite rapidly upon introduction of the potato slices into the oil by as much as $28^{o}C$ or more. The oil temperature continues to fall more gradually to a low point of about $116^{o}C$ after approximately 4 minutes. Heat to the kettle is then quickly increased and the temperature of the oil begins to gradually rise, finally reaching the initial temperature of about $150^{o}C$. (2) Batch frying of potato crisps usually takes about 13 minutes and the temperature-time profile can be found in a patent written by Henson et al. (4). It is believed that the U-shaped temperature-time profile imparts the intense flavour that some consumers find more appealing than typical continuously fried commercial crisps. (2) However Henson et al. (4) stated that the initial dehydration rate was the most important factor in providing the crunchy taste (see patent for dehydration curve), which allowed the temperature-time curve to be reduced to 8 minutes using a more efficient kettle fryer. Kettle fried potato crisps also have a final moisture content of 0.02 kg kg^{-1} or less. (4) Traditional kettle fryers are significantly constrained by burner capacity and heat transfer capacity. The oil volume, initial fry temperature, and the potato batch weight need to be tightly controlled in order to obtain the correct U-shaped temperature-time profile. Production of kettle crisps is therefore less economical and more suited to small scale operations with fryer capacities ranging from as few as 60 pounds per hour up to 500 pounds per hour, compared to continuous fryers capable of producing 1000 to 5000 pounds per hour of finished product. (5)

The oil content of potato crisps has come under focus due to health reasons. However, while low oil content is desirable for nutritional reasons, excessively low oil content levels result in poor taste and texture. The trend in the snack food industry has been to provide consumers with healthier alternatives to traditional snack foods as there is great demand for healthier snacks. (2) As well as having a crunchier taste, kettle crisps typically have lower oil contents, typically ranging between 28% and 30% compared to continuous fried crisps which typically have between 32% and 38%. Kettle crisps are sliced 1.5mm to 1.7mm thick, compared to continuous fried crisps which are usually sliced to around 1.3 to 1.4mm thick. Bernard (6) discovered that thicker crisps have lower oil uptake.

A patented new continuous cooking process has been developed by Baas et al. (5) that mimics the U-shaped temperature-time profile produced by a batch kettle fried potato crisp operation. Potato slices are placed into hot oil in a flume portion of a continuous fryer. The potato slices exit the flume into an upstream portion of the fryer. Cooling oil is injected to the upstream portion of the continuous fryer to continuously achieve the trough portion of the U-shaped temperature-tim profile. The potato slices are then further fried in the downstream portion of the fryer in a region having an increased hot oil temperature. The increased hot oil temperature occurs by injecting hot oil into the downstream portion. The temperature of the injected hot oil can be controlled by the exit moisture content of the potato slices. The oil content of the process produces crisps with oil content of 20%-23% by weight which is significantly lower than the traditional kettle-style crisp. (5)

The conventional continuously fried potato crisp still holds a dominant proportion of the potato crisp market. The demand for healthier snacks with lower oil content has provided motivation for the recent development of potato crisps produced using microwave processing. A patented technique (7) involving a microwave process has been developed to mimic the dehydration of standard continuous fried crisps to obtain a similar texture, with more control over the oil content. The potato slices are first blanched and then oil is added to the level desired for the final dehydrated product. The potato slices are then routed to a microwave dryer for explosive dehydration, mimicking the rapid dehydration process that occurs in frying. Finish drying then occurs using microwave heating were dehydration occurs at a slower rate. Although microwaved crisps are likely to be expensive compared to fried crisps (3), they could become financially viable with the possible introduction of a fat tax. Quantifying porosity, moisture content, and oil content is important for these new processing developments to optimise the cooking process and to produce high quality targeted products.

The most challenging parameter to quantify is the potato crisp solid volume fraction due to the presence of oil, closed pores, and irregular shape. The potato crisp is made up of oil, water, solid material, and air (1) as presented in Eq. 1 where v_s is the volume fraction of the solid, v_g is the volume fraction of the gas, v_w is the volume fraction of the water, and v_o is the volume fraction of the oil.

$$1 = v_s + v_g + v_w + v_o \qquad (1)$$

Porosity is defined as the "void" volume divided by the encapsulating "apparent volume" and the relationship between porosity, ϕ, and solid volume fraction is shown in Eq. 2.

$$\phi = 1 - v_s - v_w - v_o \qquad (2)$$

Porosity is an important physical property that is linked to sensory attributes such as firmness, crispiness, and crunchiness. (8) In the instance where a food product is completely saturated, and all the pores are full of water, it can be seen from Eq.2 that the food will have a porosity of zero. In most drying applications the physical space available for fluid movement is of interest. Ni et al. (9) defined "effective porosity" for modelling purposes as shown in Eq. 3. This is the total volume fraction of the gas, oil, and liquid in all the pore space (closed and open), or put another way, the space not occupied by solid structure. Effective porosity can be regarded as a more useful term than porosity as it directly indicates the amount of solid material, and the amount of space that is available for transport phenomena. The effective porosity presented in Eq. 3 has been described as the "apparent porosity" by Datta, A. K. (10) and as "net porosity" in an experimental investigation carried out by Pinthus, et al. (11).

$$\phi_{eff} = v_g + v_w + v_o = 1 - v_s \qquad (3)$$

When analysing porosity it is of course important to understand how porosity is generated. Uncooked potatoes typically contain 70–80% water and 16–24% starch. They consist of tightly packed parenchyma cells containing cytoplasm fluid, starch granules, mitochondria, golgi apparatus, amyloplasts, generative cells, and lipid droplets. (12) The pore structure of potato crisps is created during the frying process where tissue disruption/separation occurs owing to the pressure caused by the expanding water vapour. As the middle lamella pectic substances between adjacent cell walls become softened and partially solubilized by the cook treatment, the cells are forced apart. (13) (14) Reeve & Neel's (13) study showed that there are only small blisters, if any, in thin cut 1.1mm thick potato crisps (approx 6 to 8 cells deep), whereas blisters formed readily when cut to normal commercial 1.4mm thickness (approx 10-12 cells deep). Reeve & Neel (13) hypothesised that for thicker crisps, the starch in the outer cells gel and become dehydrated more rapidly than those cells in the centre of the slices. Starch gelatinisation starts at approximately 57^{o}C when swelling becomes irriversible, and may stop at approximately 95^{o}C. (14) Expanding steam is thus trapped due to the gelling of the outer surface. At first the expanding steam is principally trapped in the tiny intercellular spaces. The internal pressure increases leading to the consequent build up of swollen pockets, or blisters. Water vapour is released by the bursting of a few localised sites that break under the stress caused by pressure.

A number of studies were able to calculate the porosity of foods using measurements of true density using various pycnometric techniques, and apparent density using displacement methods. (15)' (11) The true density is shown in Eq. 4, where m_T is the total mass, V_s is the solid volume, V_w is the water volume, V_o is the oil volume, and V_t is the true volume.

$$\rho_t = \frac{m_T}{V_s + V_w + V_o} = \frac{m_T}{V_t} \tag{4}$$

The apparent density includes the air volume, V_g, as shown in Eq. 5, and can also be expressed as the total mass, m_T, divided by the total volume, V_T.

$$\rho_T = \frac{m_T}{V_s + V_w + V_o + V_g} = \frac{m_T}{V_T} \tag{5}$$

Porosity is then calculated using Equation 6. (15) (11)

$$\phi = 1 - \frac{\rho_T}{\rho_t} = 1 - \frac{V_t}{V_T} \tag{6}$$

Where V_T is the apparent volume, and V_t is the true volume.

Pinthus et al. (11) conducted a study that measured moisture content and oil content as well as total mass enabling calculation of the oil and water volumes. Measurements of true and apparent densities enabled the calculation of the true and apparent volumes using Eq. 4 and Eq. 5. This enabled Pinthus et al. (11) to quantify effective porosity using Eq. 7 below:

$$\phi_{eff} = 1 - \frac{V_t - V_w - V_o}{V_T} \tag{7}$$

Where V_T is apparent volume, V_t is true volume, V_w is water volume, and V_o is oil volume. As a result, Pinthus et al. (11) was able to plot oil pick up versus effective porosity. An oil content of 30% (wet basis) corresponded to an effective porosity of approximately 0.43 for a fried restructured potato product. The techniques used to measure oil and moisture content was destructive.

The porosity can also be calculated using apparent density if the mass fraction and density of the constituents is known as described in Eq.8.

$$\phi_{eff} = \frac{\rho_T\left(1 - f_w - f_o + \rho_g \frac{f_w}{\rho_w} + \rho_g \frac{f_o}{\rho_o}\right) - \rho_s}{\left(\rho_g - \rho_s\right)} \tag{8}$$

Where ρ_T is apparent density, f_w is the mass fraction of the water, f_o is the mass fraction of the oil, ρ_g is the air density, ρ_o is the oil density, and ρ_s is the solid density. The proof for this equation is shown in Appendix B.

The measurement of apparent density of potato crisps using displacement methods is problematic. Using liquid as a displacement medium can produce errors due to adsorption. Free flowing solid methods for measuring apparent density have potential issues relating to voids between the particulate and the food, the packing density of the particulate, and the size of the particulate in relation to sample thickness and the pore size.

X-ray micro-computed tomography, or X-ray Micro-CT can be used to visualise the solid geometry of the potato crisp and can provide a non-intrusive and non-destructive technique for accurately deducing effective porosity defined in Eq. 3.

X-ray micro-CT is a combination of X-ray microscopy and tomographical algorithms. Its principle is based on contrast in the X-ray images being generated by differences in X-ray attenuation (absorption and scattering), arising principally from differences in density within the specimen. X-rays are passed through an object along many different paths in many different directions, thus, yielding an image which displays differences in density at thousands of points in a 2D slice through the specimen. Many contiguous slices, each of a certain finite thickness, are generated in this way. (16) Finally, a computerised reconstruction is carried out. The reconstruction of the samples is based on a mathematical formalism known as the Radon transform and its mathematical framework. After processing, the CT produces a spatial description of the object under analysis where the field of view is divided into elemental digital units known as voxels. Each voxel is characterised by the attenuation coefficient of the material inside it, which is related to density. This spatial digital characterisation of the sample under analysis results in a 3D distribution of the material density within the object which allows for further digital processing of the sample. (17)

Lim & Barigou (16) carried out a Micro-CT study on aerated chocolate bar, strawberry mousse, honeycomb chocolate bar, chocolate muffin, and marshmallow were spatial cell size distribution, cell wall-thickness distribution, connectivity, and air cell volume fraction were quantified. Van Dalen et al. (18) studied the internal structures of dry crackers, coated biscuits shells, and soup inclusions. The effectiveness of moisture barrier systems was assessed using porosity data from the Micro-CT analysis to provide inputs to a moisture transport model. Esveld, et al. (19) built on work by Van Dalen et al. (18) using Mircro-CT scan data of crackers to produce 3D Computer Aided Design (CAD) geometry of the pore network for a diffusion transport model. Lassoued et al. (20) analysed scan data of bread to deduce porosity, and was able to analytically calculate density as a result. Lassoued et al. (20) found that bread had an open cellular structure, and was able to quantify mean cell size and mean wall thickness.

In order to assess porosity, subject matter is cropped so that the empty volume surrounding the porous medium is not considered in the Micro-CT porosity analysis. Unfortunately, potato crisps are too thin and irregularly shaped to analyse a meaningful cropped volume. Sometimes, the crisp is only two pores thick. This study uses a novel technique to determine the effective porosity of three types of potato crisp using Micro-CT scan data. Standard continuously fried crisps, continuously fried kettle crisps, and proprietary microwaved crisps were analysed. As means of comparison, porosity is also calculated for continuous fried potato crisps using apparent density measurements, where apparent density was measured using displacement of rapeseed and ceramic beads.

The microwave process was designed to replicate the continuous frying process to produce a potato crisp with the same structure and taste, whilst retaining control of the oil content. While the Micro-CT study was used to check the similarity of the potato crisp porosity, a forced preference test was used to check if the taste of the continuous fried potato crisp had been replicated using the microwave process.

MATERIALS AND METHOD

As comparison to the Micro-CT technique, the apparent density of continuous fried potato crisps was measured using displacement of free flowing solids, initially with rapeseed of 2mm diameter, and then with ceramic beads of 0.5mm diameter. Six measurements were carried out using each free flowing media. The displacement measurements were carried out using the method described by Segnini *et al.* (21) In each instance the mass of the free flowing solid was measured without potato crisps to assess repeatibility of packing density. When using ceramic beads as the displacement medium, it was important to break the crisps to smaller sizes of approximatley 5x5mm. This greatly reduced the potential for voids that can occur under the irregularly shaped crisp during measurment. This was required because the ceramic beads did not flow as freely as rapeseed. It also enabled the ratio of crisp to free flowing solid to be increased which decreased experimental error.

Water mass fraction of the continuous fried potato crisps was measured gravimetrically through exposure to 4 litres/min of dry nitrogen in a descciator until mass equilibrium had been obtained. The mass measurement interval was 2 weeks and twelve sample dishes were measured in the dessicator, each containing approximately 2.4 grams of potato crisp. Oil mass fraction was provided by the manufactuer and is published on the potato crisp packaging. The oil density was measured by pouring oil into a measuring beaker to a set volume, and weighing the gain in mass.

The solid potato density was calculated using Eq. 8, which is an equation that can be used for uncooked potato, where ρ_T is the apparent density, f_w is the mass fraction of the water, and ρ_w is the density of water. The apparent density of uncooked potato was measured to be 1055kgm^{-3} through water displacement of peeled potatoes (3 replicates), and the mass fraction of water was measured to be 82.2% by oven drying at 105^{o}C for 24 hours (3 replicates). The proof for Eq. 9 can be found in Appendix A.

$$\rho_s = \frac{1-f_w}{\frac{1}{\rho_T}-\frac{f_w}{\rho_w}} \tag{9}$$

In the Micro-CT study, six crisps were scanned using a high resolution desktop X-ray Micro-CT system, Skyscan 1172 (Skyscan, Kontich, Belgium), which consists of a microfocus sealed X-ray tube operating at a voltage of 60 kV and current of 163 μA. The X-ray detector consists of a 1024 x 1024 pixels 12-bit digital cooled Charge-Coupled Device (CCD) camera. The micro-CT system used is schematically represented in Fig. 1. The six potato crisps scanned were provided by Walkers (PepsiCo Inc., UK) and consisted of three different potato crisp types, two of each type. The three types of potato crisp scanned were standard fried potato crisps, microwaved potato crisps, and continuous kettle fried potato crisps.

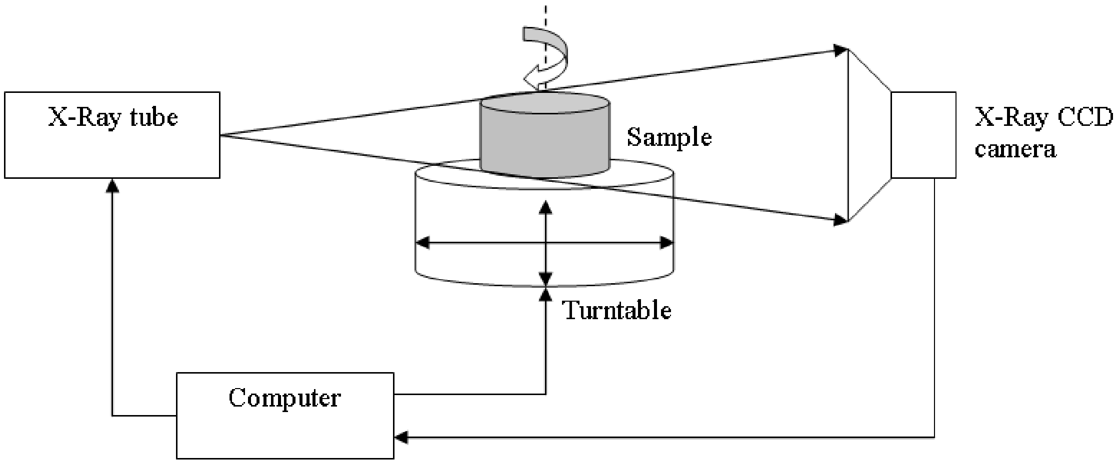

Fig. 1 - Schematic diagram of Micro-CT system

Each crisp sample scanned was approximately 7mm x 5.8mm x 1mm. The scanned samples were wrapped in parafilm to prevent oil from contaminating the sample cavity. The images were reconstructed using hierarchical InstaRecon® software to produce a stack of 2D images, each 2.52µm apart (voxel size). One of the reconstructed images is shown in Fig. 2.

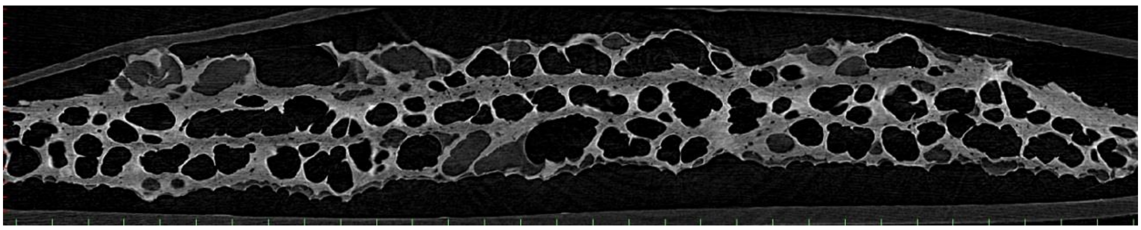

Fig. 2 - Re-constructed image forming part of a 2D image stack were each notch on the horizontal axis is 250µm

The image stack was then imported into Mimics® (Materialise, Leuven, Belgium), an image processing program that can be used for segmentation and generation of 3D models from Micro-CT data. Each crisp had to be split into sections along the 5.8mm dimension for data handling purposes. The greyscale range of the solid potato material was selected to produce a mask, or binary image of the solid phase. This was selected manually using the clear distinction between solid and fluid greyscale caused by the large difference in density. The density of the constituent materials can be used to indicate the ease at which an accurate range of greyscale can be manually selected for the solid material. The density of the solid material was measured to be 1434kgm^{-3} which is significantly higher than oil which was measured to be 910kgm^{-3}, and water which is known to be 998.2kgm^{-3}. (22)

The mask can include specs floating in space that are not connected to the main body. This is caused by noise captured within the greyscale threshold. To remove noise and artefacts the main body of the mask was selected and separated from areas of the mask that were not connected. In some instances the mask had to be manually edited to deselect pixels connecting the crisp from the parafilm wrap. Because the oil surrounds the crisp and is not part of the mask, there were instances where the parafilm wrap was only joined to the crisp by one pixel. In these instances, the mask was eroded by 1 pixel, the crisp could then be separated from the parafilm wrap, and the mask of the crisp was then dilated back by 1 pixel to its original size. A mask generated on one of the 2-D image slices is shown in Fig. 3. Each notch on the horizontal grid in Fig. 2 corresponds to 250µm; hence the horizontal length of the image is 7.75mm.

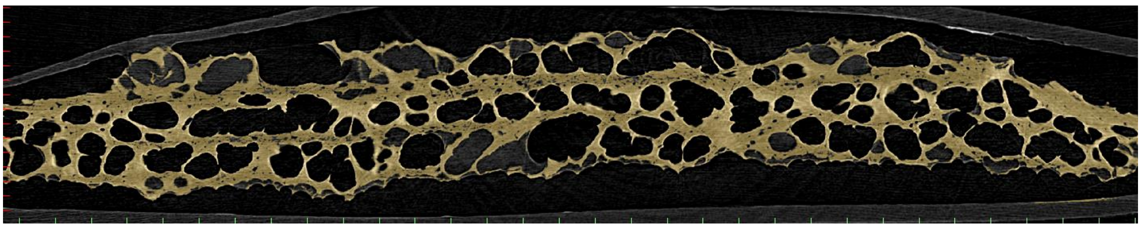

Fig. 3 - Mask applied to 2D image stack to represent the solid potato structure, each notch on horizontal axis is 250µm

The solid potato mask was then used to produce 3D CAD geometry of the potato crisp segment, as shown in Fig. 4. Typically, porosity would be calculated by subtracting the solid volume from the total cropped volume, and then dividing by the total cropped volume. However, in this study the cropped scan of 2D slices includes large areas of air that sit outside of the potato crisp. Therefore a new method had to be devised to calculate the porosity. The CAD geometry of the porous medium was exported into 3-Matic® (Materialise, Belgium) where a "wrap" operation was carried out to determine the apparent volume of the potato crisp segment. Wrap operations are available in a number of commercially available CAD programs. The operation encapsulates the geometry and is analogous to wrapping the geometry in a blanket to cover up gaps. It is usually used to create water tight volumes from CAD geometry that may otherwise contain small gaps or imperfections. The maximum size of gap that is bridged by the wrap operation can be specified, which in this case corresponded to the maximum opening pore size on the external potato crisp surface. This ensures that the wrap covers the external surface only, and was determined approximately using a linear measurement tool on 2D slices in Mimics® (Materialise, Belgium). The wrap operation was visually inspected once it was generated to make sure that all the largest pore openings on the external surface had been bridged. The wrap operation carried out for this potato crisp segment is presented in Fig. 5. Parts of the wrap are concave, where it covers large pores, and other parts of the wrap encapsulate too much volume as it covers peaks in the solid, like a pitched tent.

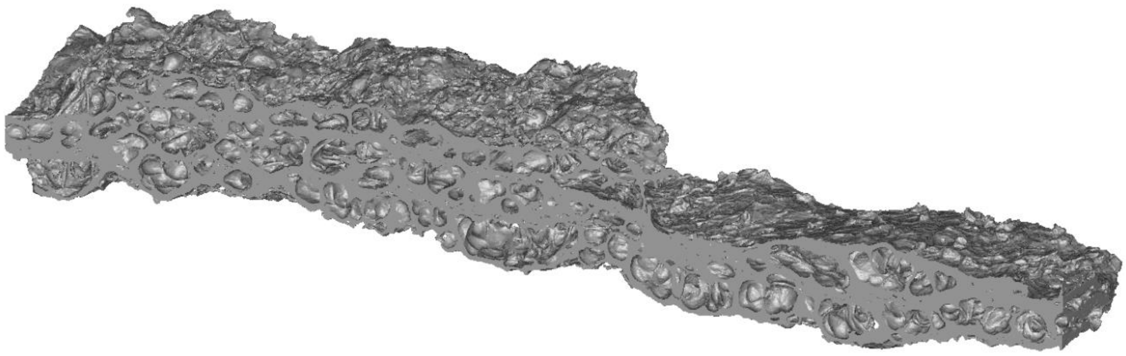

Fig. 4 - Three dimensional CAD geometry of a segment of solid potato crisp structure generated from Micro-CT scan data

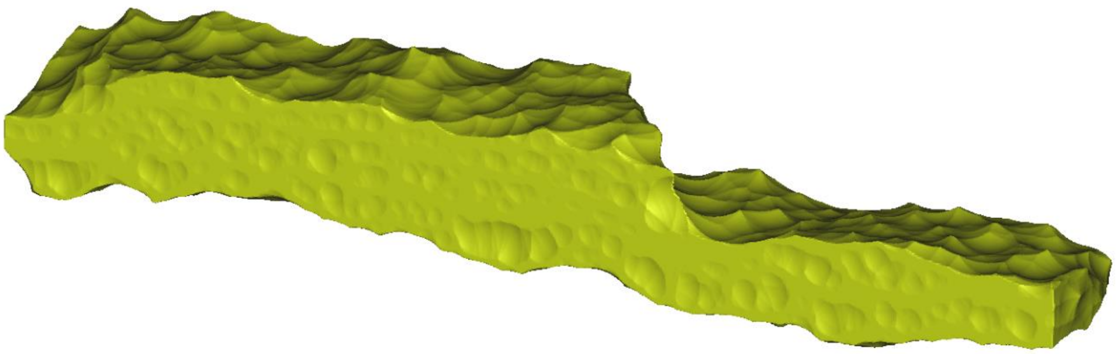

Fig. 5 - Micro-CT geometry wrapped to deduce the apparent volume

The volume of the solid (Fig. 4) and the apparent volume of the same potato crisp (Fig. 5) now exist in CAD as separate watertight volumes. These volumes can be quantified by the CAD package using standard functionality. Nearly all CAD packages are able to deduce volumes of CAD geometry accurately, especially in this case due to the number of vertices contained within the geometry. The effective porosity can be calculated using the following formula, where V_T is the apparent volume of the potato crisp and V_s is the volume of the solid porous potato structure.

$$\phi_{eff} = \left(V_T - V_s\right) / V_T \qquad (9)$$

The forced preference consumer test was carried out with the microwaved potato crisps and the continuous fried potato crisps. The test was carried out with 200 people who were selected to be balanced across gender, age (<35, >35), socio-economic grouping, and eating frequency.

RESULTS AND DISCUSSION

The measured apparent density of standard continuous potato crisps using rapeseed displacement was 377kgm^{-3} with a standard deviation of 82kgm^{-3}, which is 22% of the mean. This result is similar to the apparent density measured by Segnini *et al*. (21) using rapeseed displacement, which ranged from 380kgm^{-3} to 450kgm^{-3} for a range of commercial potato crisps. The measured apparent density using ceramic beads displacement was 935kgm^{-3} with a standard deviation of 94kgm^{-3}, which is 10% of the mean. The variation in packing density for the rapeseed was measured to be 0.2% whilst it was only 0.1% for the ceramic beads. Inaccuracies are likely to be caused by the rapeseed diameter, which at 2mm is twice that of potato crisp thickness. Not only is this an issue with respect to thickness, but it means that the rapeseed can only contact the potato crisp every 4mm, which is not enough to take into account some surface features. The ceramic beads result is likely to be more accurate, however the size of the beads is 0.5mm, and study of the Micro-CT images generated in this study shows that some of the open pores on the surface of the crisp are of a similar size. Hence there is the risk that some beads could lay within the potato crisp during measurement, which could result in an artificially higher apparent density.

The mass fraction of oil, f_o is 0.323kg.kg^{-1}, the water mass fraction f_w was measured to be 0.017kg.kg^{-1}, the density of oil, ρ_o, was measured to be 910kgm^{-3}, the density of solid potato was measured to be 1434kgm^{-3}. The measured density of the solid potato material is very close to the value of 1419kgm^{-3} presented in literature (10)' (23). The density of water is 998.2kgm^{-3} and the density of air is 1.2kgm^{-3}. (22) Using these values with the measured apparent density of 935kgm^{-3}, the effective porosity was analytically calculated using Eq. 8 to be 0.57. This value is likely to be slightly low due to the experimental error caused by some of the ceramic beads entering the potato crisp open pores during density measurement.

The effective porosity results for each segment of the six potato crisp samples analysed using Micro-CT is presented in Table 1, along with the average effective porosity and standard deviation.

The average effective porosity of the standard fried potato crisps is 0.627 with a standard deviation of 0.032. A reasonably large standard deviation is expected for fried potato crisps. There is temperature variations in the fryer and each crisp will be subjected to different frying conditions as it finds a different path through the continuous fryer. The effective porosity value of 0.627 obtained through Micro-CT analysis is higher than the effective porosity value of 0.57 calculated using the apparent density measured using ceramic bead displacement. As previously discussed, the 0.57 effective porosity value is likely to be low due to experimental error caused by apparent density measurement.

The microwave process is designed to replicate the frying process, so it is important that the effective porosity, and the taste of the microwaved crisp, does not deviate too much from the continuous fried potato crisp. The effective porosity of the microwaved potato crisp is 0.653, which is very similar to the effective porosity of 0.627 for the continuous fried potato crisp. This similarity in effective porosity helps demonstrate the success of the microwave process. The results of the forced preference survey showed that the microwaved dehydrated product was preferred by 51% which allows us to conclude that consumers equally preferred microwaved potato crisps and standard fried crisps. The microwave process was designed to imitate the dehydration process in the continuous fryer, and it can be deemed to be very successful in terms of final crisp effective porosity and taste. The Micro-CT results show that the variation in effective porosity is lower for the microwaved crisp at 2.8% of the mean as opposed to 5.1% of the mean for fried crisps.

The continuous fried “Kettle” crisps, manufactured using a process that mimics batch frying, have a markedly lower effective porosity at 0.543 compared with the standard continuous fried crisps (0.627), and the microwaved crisps (0.653). It can be seen visually from the Micro-CT scan images in Fig. 6 that the continuous kettle fried crisp has a larger solid volume fraction, and that the standard continuous fried crisp has a higher effective porosity. The frying time of kettle crisps is longer at 7-9 minutes, and the oil temperature is lower throughout the process at 150^{o}C to 110^{o}C, compared to 2.5 to 3 minutes at 185^{o}C for continuous fried crisps. (5) (2) A longer frying time at lower temperature would result in less explosive dehydration. It stands to reason that less explosive dehydration seen in frying of kettle crisps would produce a lower effective porosity. A lower effective porosity signifies more solid material which is likely to be a driving factor behind the crunchy taste for which kettle crisps are known. The lower oil update of thicker crisps observed by Bernard (6) may be evidence of lower porosity. Most oil uptake occurs post frying (24) and it is intuitive that a lower void volume would suck in less oil.

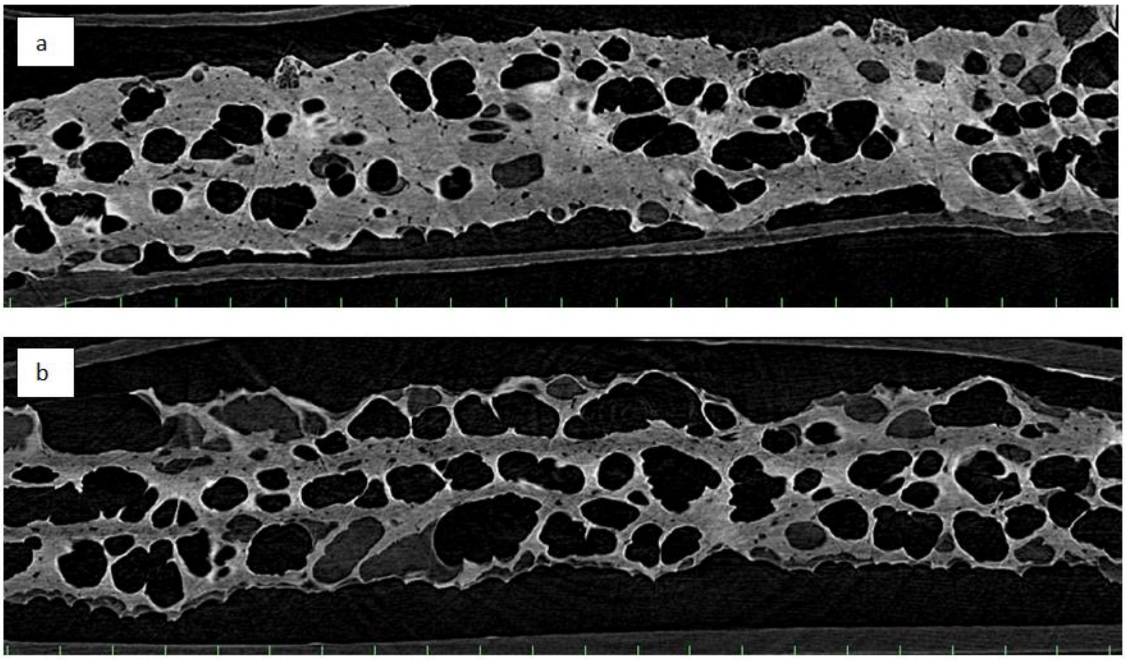

Fig. 6 - Micro-CT generated 2D image of (a) continuous fried kettle crisp, and (b) standard continuous fried crisp bottom, each notch on horizontal axis is 250µm

The standard deviation of the effective porosity for the kettle crisp is 12.4% of the mean, which is a lot higher than the other two crisp types. The kettle frying process is inherently more variable than the standard continuous frying technique due to large variations in temperature during frying, which is likely to cause more variation in porosity. The start of the kettle frying process is particularly likely to cause variation in temperature as a large batch of raw unwashed potato slices is introduced into a hot kettle of oil causing a U shaped temperature profile. (2) Conversely continuous fried crisps enter the fryer on a continuous conveyor and the frying temperature is kept constant to +/-2^{o}C.

CONCLUSIONS

This study shows how a novel technique for assessing effective porosity can be used to gain insights into product quality. The effective porosity, and variation in effective porosity, can be used to quantify the effect different cooking processes have on the product structure. The effective porosity data obtained reflects development of cutting edge production techniques, controlling the temperature-time curve and dehydration rate to deliver specific product attributes. “Kettle” crisps produced using a continuous fryer that mimicked the batch frying process, have a low effective porosity of 0.54 which corresponds to the desired crunchy taste of batch fried “kettle” crisps. The effective porosity had a standard deviation of 0.067 which was high compared to standard continuously fried crisps. High variation is indicative of the traditional batch frying process due to the highly variable oil temperature in the cooking process. Fried potato crisps and potato crisps microwave dehydrated to mimic the drying profile of fried potato crisps had very similar effective porosities of 0.63 and 0.65 respectively. In a forced preference consumer test (n=200), there was no statistically significant difference in preference (51% preferred the microwaved crisp).

ACKNOWLEDGEMENTS

The authors would like to thank E2v technologies for funding this research, Steve Hurrell, Jan Przybyla, Adam Taylor, and Stephen Spark for their support, and Mike Spurr for samples and product information.

Appendix A

The total density of potato is the total mass divided by the total volume.

$$\rho_T = \frac{m_T}{V_T} \qquad \text{(A.1)}$$

Potato is made from solid material, and water, hence Eq. A1 can be described as follows.

$$\rho_T = \frac{m_T}{V_w + V_s} \qquad \text{(A2)}$$

The water and solid volume are described in Eq. A3 and Eq. A4 respectively

$$V_w = \frac{m_w}{\rho_w} \qquad \text{(A3)}$$

$$V_s = \frac{m_s}{\rho_s} \qquad \text{(A4)}$$

Substituting Eq. A3 and Eq. A4 into Eq. A2.

$$\rho_T = \frac{m_T}{\frac{m_w}{\rho_w} + \frac{m_s}{\rho_s}} \qquad \text{(A5)}$$

The mass of water and the mass of the solid material can be expressed in terms of mass fraction as shown in Eq. A6 and Eq. A7 respectively.

$$m_w = f_w m_T \qquad \text{(A6)}$$

$$m_s = f_s m_T \qquad \text{(A7)}$$

Substituting Eq. A6 and Eq. A7 into Eq. A5, and then re-arranging to make the density of the solid the subject:

$$\rho_T = \frac{m_T}{\frac{f_w}{\rho_w} + \frac{f_s}{\rho_s}}$$

$$\rho_s = \frac{f_s}{\frac{1}{\rho_T} - \frac{f_w}{\rho_w}} \qquad \text{(A8)}$$

It is assumed that solid potato is made from two constituents, water and solid potato material as shown in Eq. A9

$$f_s = 1 - f_w \quad \text{(A9)}$$

Substituting Eq. A9 into Eq. A8:

$$\rho_s = \frac{1-f_w}{\frac{1}{\rho_T} - \frac{f_w}{\rho_w}} \quad \text{(9)}$$

Appendix B

The potato crisp consists of solid potato, oil, water, and air. Therefore the total mass of the potato crisp is described as follows:

$$m_T = m_s + m_w + m_o + m_g \quad \text{(B.1)}$$

This can be expressed in terms of volume and density as shown below

$$m_T = \rho_s V_s + \rho_w V_w + \rho_o V_o + \rho_g V_g$$

$$\frac{m_T}{V_T} = \rho_s \frac{V_s}{V_T} + \rho_w \frac{V_w}{V_T} + \rho_o \frac{V_o}{V_T} + \rho_g \frac{V_g}{V_T}$$

$$\rho_T = \rho_s v_s + \rho_w v_w + \rho_o v_o + \rho_g v_g \quad \text{(B.2)}$$

If the crisp is made up of oil, water, and solid material, then the remaining volume fraction is made up of gases as described below:

$$v_g = 1 - v_o - v_w - v_s \quad \text{(1)}$$

Substituting Eq. 1 into Eq. B.2

$$\rho_T = \rho_s v_s + \rho_w v_w + \rho_o v_o + \rho_g (1 - v_o - v_w - v_s) \quad \text{(B.3)}$$

Effective porosity is defined in Eq. 3

$$\phi_{eff} = 1 - v_s \quad \text{(3)}$$

Substituting Eq. 3 into Eq. B.3:

$$\rho_T = \rho_s (1 - \phi_{eff}) + \rho_w v_w + \rho_o v_o + \rho_g (\phi_{eff} - v_o - v_w) \quad \text{(B.4)}$$

The specific volume of oil and water can be described in terms of mass fraction as shown in Eq. B5 and Eq. B6 respectively.

$$v_o = f_o\left(\rho_T / \rho_o\right) \tag{B.5}$$

$$v_w = f_w\left(\rho_T / \rho_w\right) \tag{B.6}$$

Substituting Eq. B.5 and Eq. B.6 into Eq. B.4 and then re-arranging to make effective porosity the subject.

$$\rho_T = \rho_s\left(1-\phi_{eff}\right) + \rho_T f_w + \rho_T f_o + \rho_g\left(\phi_{eff} - f_o\frac{\rho_T}{\rho_o} - f_w\frac{\rho_T}{\rho_w}\right)$$

$$\rho_T = \frac{\rho_s\left(1-\phi_{eff}\right) + \rho_g\phi_{eff}}{\left(1 - f_w - f_o + f_o\frac{\rho_g}{\rho_o} + f_w\frac{\rho_g}{\rho_w}\right)}$$

$$\phi = \frac{\rho_T\left(1 - f_w - f_o + \rho_g\frac{f_w}{\rho_w} + \rho_g\frac{f_o}{\rho_o}\right) - \rho_s}{\left(\rho_g - \rho_s\right)} \tag{8}$$

REFERENCES

1. Rodríguez-Ramíez J, Méndez-Lagunas L, López-Ortiz A, Torres SS. True density and apparent density during the drying process for vegetables and fruits: A review. Journal of food science. 2012; 77: p. 145-154.
2. Desai PM, Jones AS, Mathew R, Neel DV, Vogel G, Wright S, inventors; Method for Reducing the Oil Content of Potato Chips. US patent US8808779 B2. 2014.
3. Schiffmann RF. Microwave processes for the food industry. In Datta AK, editor. Handbook of microwave technology for food applicatons. New York - Basel: Marcel Dekker; 2001. p. 299-337.
4. Henson WD, Slovak WR, Dalson CT, Slay BD, inventors; Process for producing kettle-style potato chips. US patent US5643626 A. 1997.
5. Baas IA, Barry DL, Beasley GR, Olds JW, Rossiter ND, Samuels RD, et al., inventors; Potato slices fried in hot oil in a flume portion of a continuous fryer, exit the flume into an upstream portion where cooling oil is injected to form the trough portion of a U-shaped temperature-time profile, then further fried in the downstream. US patent US7303777 B2. 2007.
6. Bernard DC, inventor; Method of preparing low oil fried potato chips. US patent US4537786 A. 1985.
7. Bows JR, Burnham CJ, Coker JP, Hilliard GP, Hickie DL, Lock ML, et al., inventors; Preparing shelf-stable food slices by thermally preconditioning a plurality

of food slices and rapidly dehydrating slices to a moisture content of less than 20% with a microwave; reduced oil potato crisps having desirable organoleptical properties. US patent US7695746 B2. 2010.

8. Guessasma S, Chaunier L, Della Valle G, Lourdin D. Mechanical modelling of cereal solid foods. Trends in food science and technology. 2011; 22: p. 142-153.
9. Ni H, Datta AK, Torrance KE. Moisture transport in intensive microwave heating of biomaterials: a multiphase porous media model. International Journal of Heat and Mass Transfer. 1999; 42: p. 1501-1512.
10. Datta AK. Porous media approaches to studying simultaneous heat and mass transfer in food processes II: Property data and representative results. Journal of food engineering. 2007b; 80: p. 96-110.
11. Pinthus EJ, Weinberg P, Saguy IS. Oil uptake in deep fat frying as affected by porosity. Journal of food science. 1995b; 60: p. 767-769.
12. Bordoloi A, Kaur L, Singh J. Parenchyma cell microstructure and textural characteristics of raw and cooked potatoes. Food Chemistry. 2012; 133: p. 1092–1100.
13. Reeve RM, Neel EM. Microscopic structure of potato chips. American potato journal. 1960; 37(2): p. 45-52.
14. Costa RM, Oliveira FAR, Boutcheva G. Structural changes and shrinkage of potato during frying. International journal of food science and technology. 2001; 36: p. 11-23.
15. Krokida MK, Oreopoulou V, Maroulis ZB. Effect of frying conditions on shrinkage and porosity of fried potatoes. Journal of food engineering. 2000; 43: p. 147-154.
16. Lim KS, Barigou M. X-ray micro-computed tomography of cellular food products. Food research international. 2004; 37: p. 1001-1012.
17. Lin CL, Videla AR, Miller JD. Advanced three-dimensional multiphase flow simulation in porous media reconstructed from X-ray Microtomography using the He-Chen-Zhang Lattice Boltzmann Model. Flow measurement and instrumentation. 2010; 21: p. 255-261.
18. Van Dalen G, Nootenboom P, Van Vliet LJ, Voortman L, Esveld E. 3-D imaging, analysis and modelling of porous cereal products using X-Ray microtomography. Image analysis and stereology. 2007; 26: p. 169-177.
19. Esveld DC, Van Der Sman RGM, Van Duynhoven JPM, Meinders MBJ. Effect of morphology on water sorption in cellular solid foods. Part I: Pore scale network model. Journal of Food Engineering. 2012; 109: p. 301-310.
20. Lassoued N, Babin P, Valle GD, Devaux M, Réguerre A. Granulometry of bread crumb grain: Contributions of 2D and 3D image analysis at different scale. Food research international. 2007; 40: p. 1087-1097.
21. Segnini S, Pedreschi F, Dejmek P. Volume measurement method of potato crisps. International journal of food properties. 2004; 7: p. 37-44.
22. Rogers GFC, Mayhew YR. Thermodynamic and transport properties of fluids. 5th ed. Oxford: Blackwell Publishers; 1964.
23. Rahman MS. Food properties handbook. 2nd ed. Boca Raton: CRC Press; 2009.
24. Bouchon P, Pyle DL. Modlling oil adsorption during post frying cooling I: Model development. Trans IChemE, Part C, Food and bioproducts processing. 2005; 83: p. 253–260.

Type of crisp	Effective porosity of segments from crisp sample 1	Effective porosity of segments from crisp sample 2	Average effective porosity of potato crisp segments	Standard deviation of effective porosity of potato crisp segments	Standard deviation of effective porosity as percentage of the mean
Standard packaged fried potato crisps	0.615	0.627	0.627	0.032	5.1%
	0.606	0.671			
	0.613	0.68			
	0.604	0.654			
	0.581	0.615			
Packaged microwaved potato crisps	0.659	0.625	0.653	0.018	2.8%
	0.656	0.651			
	0.679	0.629			
	0.664	0.664			
Packaged continuous Kettle fried thick potato crisps	0.641	0.558	0.543	0.067	12.3%
	0.622	0.59			
	0.538	0.56			
	0.441	0.493			
	0.45	0.533			

Table 1 Effective porosity obtained from Micro-CT analysis