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A microscopic computer vision algorithm for autonomous bubble detection in aerated complex liquids

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ABSTRACT

The size distribution of bubbles in cake batters is often determined from optical microscopic imaging, considering the lesser availability and non-affordability of sophisticated techniques such as light scattering, and acoustic methods. We present an automated bubble detection and counting method from microscopic images that presents flexibility and robustness over existing manual approaches. The method is able to successfully resolve connected bubbles and recognise far many bubbles in an image than would be possible by naked eye or hitherto reported methods in chemical and food engineering literature. Furthermore, the size data obtained for the bubbles can easily be used for routine statistical analysis. We demonstrate the application of our method for studying the influence of two different mixer geometries and three different speeds on bubble size.

1. Introduction

The bubble size distribution in viscous aerated foods has a large effect on their bulk physical properties (Labbafi et al., 2007). The size distribution of bubbles depends on the process of gas infusion, product viscosity and mixing technology. Mixing and homogenizing of viscous foods such as cake batters, provides uniform distribution of bubbles over the volume; however this discrete structure is not stable over time. In Angel cakes and similar recipes, the bubbles remain relatively discrete as the high viscosity of the continuous phase retards coalescence (Chesterton et al., 2013). Despite widespread practice of bubble inclusion into foods as unit operation, bubble size distribution has received relatively little research attention.

Batters are highly viscous liquids with a dispersion of numerous bubbles of wide ranging sizes and are commonly designated as complex liquids (Misra and Tiwari, 2014; Van der Sman, 2012). Consequently, they do not allow sufficient light transmission during imaging microscopy. In addition, if the sample on a glass slide is thicker than the typical diameter of the bubbles, refraction of light and noise from other dissolved substances become challenging. The challenges turn even more prominent when bubbles overlap. To increase the visibility under a light microscope, Sahi and Alava (2003) recommended placing the sample between two microscope glass slides. However, this approach affects intact food structure and considerably raises the probability of bubble coalescence due to compression and formation of liquid bridges because of capillary forces. Thus, direct observation of undisturbed batter samples, placed on microscopic slides is preferable.

Traditionally, bubble size quantification in cake batters has been performed by manual detection and counting of bubbles available from light microscopy images. A summary of the experimental studies in literature employing microscopic image analysis of batters is provided in Table 1. Massey et al. (2001) employed a horizontal pressure whisk aerator at 102 rpm and 300 rpm, whereas Chesterton et al. (2013) employed a vertical wire whisk planetary aerator at 61, 125, and 259 rpm. The traditionally employed microscopic methods are time consuming and subject to both human error and experimenter bias. Automation of the measurement process has the potential to improve the accuracy of the measurements, considerably reduce the time required for analysis, and promote reporting of size distribution data by food researchers. Moreover, an increasing number of research topics and applications in chemical, food and pharmaceuticals demand a precise measurement of the bubble and particle size distribution in liquids through reliable and automated image analysis (Arnaout et al., 2016).

In this work, an automated approach to obtain bubble size distribution from microscopic images that overcomes many of the limitations of existing methods is presented. The method enables to detect bubbles in noisy images obtained from direct microscopic imaging of translucent batters, whereas earlier methods required batter handling for long durations (Sahi and Alava, 2003). Our approach is robust,

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Nomenclature

$\overline{P}$	Perimeter of the region
μ	Mean of the log-normal distribution
μ_g	Geometric mean of the distribution
σ	Standard deviation of the log-normal distribution
σ_g	Geometric standard deviation of the distribution
A_R	Area of the region
$b(x, y)$	Binary image
d_b	Mean bubble diameter, μm
D_i	Midpoint of the i-th class in the histogram of bubble sizes
D_{eq}	Equivalent diameter of the region
$f(D_i)$	Probability density function of D_i
$R(x, y)$	Image region
Th	Threshold value

Table 1
Bubble sizes reported from analysis of optical microscopy images of batters. (Emul.: Whether emulsifier added; d_b = Mean bubble diameter).

Batter type	Emul.	Size (μm)	Mixing/Time (rpm/min)	Source
Sponge cake	Yes	d_b = 70-110	Whisk (102, 300/2–30)	Massey et al. (2001)
Sponge cake	No	d_b = 35-50	Whisk (102, 300/2–30)	Massey et al. (2001)
Sponge cake	Yes	d_b = 20-50	Rotor-stator (300/n.a.)	Sahi and Alava (2003)
High ratio	No	d_b = 25-45	Whisk (61, 125, 259/0–10)	Chesterton et al. (2013)
High ratio	Yes	d_b = 7-29	Whisk (61, 125, 259/0–10)	Chesterton et al. (2013)

flexible and has the ability to detect maximum number of bubbles, without the requirement of any human intervention to trace the bubble boundaries (Massey et al., 2001; Jakubczyk and Niranjan, 2006). The method is free from any approximation with regards to the minimum or maximum bubble size, as with Hough transformation (HT) based methods. In addition, it allows to eliminate the need for expensive computer hardware, enabling the method to be used more routinely and effectively in food research laboratories. To demonstrate the real-world applicability of the method, the effects of mixer geometry and the mixing speed on the bubble size distribution in a non-ideal cake batter system is quantified.

2. Experiments

2.1. Batter preparation

The composition (%w/w) of the non-ideal, model batter prepared for all studies described in this work is as follows: flour (28%), sugar (31.5%), egg white powder (6%), ammonium bicarbonate (0.5%), and water (34%). The batter was prepared by mixing the ingredients in a Hobart bench-top mixer at low speed (60 rpm) for 1 min, followed by 5 min of mixing at slow (60 rpm) or intermediate (125 rpm) or high speed (250 rpm), depending on the experiment. The specific gravity of the model batters prepared for this work ranged between 0.9 and 1.08 (in the order of chocolate and other "rich" cakes), depending on the mixing process. However, for other commercial batter formulations, under similar aeration conditions, the specific gravity could range between 0.5 and 0.9, as with sponge and angel cakes. Experiments were carried out using two different mixing elements, viz. a wire whip, and a flat beater to compare the resulting effects (see Fig. 1). For each experiment a 1 kg batch of the batter sample was freshly prepared. Details of the experimental conditions are provided in Table 2.

2.2. Image acquisition

The batters to be analysed were prepared for microscopy immediately after mixing. Two microscopic slides were prepared for each sample and four images from different non-overlapping spatial locations were acquired per slide. For sample preparation for microscopy, a drop of the batter was placed on a glass slide and allowed to spread by holding the slide in a slanted position. The sample was not covered by a cover glass to prevent the bubbles from flattening and thereby increasing the chances of coalescence. Slides were observed under an optical microscope (Olympus CX41, USA) with a 10× magnification objective lens. A digital camera (QImaging Micropublisher 3.3 RTV, BC, Canada) was mounted on the microscope, and in turn connected to a personal computer. Images were acquired at 925 × 694 pixels and stored using QCapture Pro 7 software (QImaging, BC, Canada). For calibration, a transparent micrometer scale was employed to determine the number of pixels per measured physical length. The process of sample preparation and image acquisition altogether required less than 3–4 min. When thin films of batter are left open to ambient conditions for more than 7–8 min, drying effects become pronounced. It should be noted that such a loss of moisture may affect the matrix properties and thus, the bubble dynamics (e.g., disproportionation rate).

3. Image analysis

An algorithm for the automated detection and morphological measurement of the bubbles in the image was developed. A Computer code for the image analysis algorithm was scripted in MATLAB™ (The Mathworks Inc, MA). The algorithm for bubble detection in the images involved the following steps: preprocessing, thresholding, distance transformation, watershed segmentation, feature screening to detect the bubbles, and analysis of the features detected. Detailed accounts of the algorithm are provided in the following subsections.

3.1. Pre-processing

The image pre-processing step involved conversion of the red, green and blue (RGB) channel images into HSV (hue, saturation and value), followed by extraction of the value matrix (V-channel) for all further processing. Each pixel of the V-channel image was squared to emphasize the darker objects, followed by median filtering to remove the "salt

Fig. 1. The wire whip (left), and the flat beater (right) mixer geometries.