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Modelling of shear rate distribution in two planetary mixtures for studying development of cake batter structure

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ABSTRACT

The shear rate experienced by a fluid near the wall of a planetary mixer when agitated by a wire whisk tool has been estimated using a simple geometrical analysis. The bowl and whisk geometries were measured for a Kenwood KM250 and a Hobart N50 mixer which are in widespread use in domestic and laboratory installations. The shear rate is shown to be a maximum at the bowl wall. This value is relatively uniform over a large fraction of the wall height, except for a small volume near the base and the region above the maximum width of the mixer. The shear rate profile is sensitive to the vertical positioning of the agitator within the bowl. For standard manufacturer speed settings, the range of maximum shear rates was estimated to be 100-500 s^{-1} in the Hobart and 20–100 s^{-1} in the Kenwood.

1. Introduction

Mixing is a key step in many manufacturing processes as this is used both to combine ingredients and to generate microstructure. Understanding the impact of processes such as mixing on product structure is essential for process improvement and the effect can be quantified by determining rheological properties (Cullen and O'Donnell, 2009). Industrial processing can involve a wide range of shear regimes (Table 1): it is therefore important to know the magnitude and range of shear rates experienced by the material during mixing for (i) relating results from different types of mixer (e.g. in comparing results from different laboratories), (ii) scaling up from laboratory to factory scales, and (iii) determining the relevant range of shear rates for rheological measurement.

Planetary mixers are often used in domestic, laboratory and industrial applications to prepare food and other soft solid materials. To our knowledge the shear rates developed in these devices have not been quantified. Rotational and beater tip speeds are reported but these are not direct indicators of shear rate. We report an approximate method for calculating representative shear rates generated in two widely-used laboratory mixers (namely a Kenwood KM250 and a Hobart N50 mixer).

Our particular interest lies in the preparation of cake batters, where planetary mixers are widely used to combine solid and liquid ingredients to form a liquid matrix and then to incorporate air by vigorous mixing. In a companion paper (Chesterton et al., 2011) the information on shear rates is used to inform an investigation of the development of structure in aerated cake batters.

1.1. Planetary mixing

Planetary mixers are batch devices which use a characteristic whisking motion created by two simultaneous rotations. This arrangement allows the entire mixed volume to receive a vigorous beating action and ensures efficient mixing whilst minimising agitator diameter, and avoiding high specific power consumption and temperature rises (Niranjan et al., 1994). Planetary mixing is popular in many industrial applications, particularly within the pharmaceutical and food industries, as it is a reliable and robust way of homogeneously mixing solid–liquid systems (Hiseman et al., 2002). It is also commonly used in laboratory studies and domestic applications, as the volume of material can be varied readily and the progress of mixing monitored visually. Bakeries often use planetary type vertical mixers for the preparation of sponge batters. Many development or test bakeries use this type of machine to develop a product even though a continuous machine might be used for production purposes (Cauvain and Cyster, 1996).

Scaling up mixing processes from small scale batch studies to larger devices with different geometries remains a major challenge in mixing and powder technology (Delaplace et al., 2007). Classical measures of mixing performance such as modified power numbers and Reynolds numbers have been reported (e.g. Delaplace et al., 2005) but the difficulty lies in linking mechanical action to micro-scale attributes such as distribution of components (e.g. in solids mixing) or development of microstructure in the materials

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Nomenclature

A	point on whisk perimeter of maximum diameter
B	attachment axis of rotation
C	centre of bowl
D	arbitrary point on whisk perimeter
H_A	height of maximum radius on whisk tool, mm
H_h	height of Hobart mixer bowl, mm
H_k	height of Kenwood mixer bowl, mm
r	radius of rotation of attachment shaft about the bowl centre, mm
R	radius of rotation of attachment shaft about its own axis, mm
t	time, s
V_D	velocity of point D, m s^{-1}
x, y	Cartesian co-ordinates, Fig. 3
z	height within the bowl, mm
Ω_r	rotational speed of the shaft about the bowl centre, rad s^{-1}
Ω_R	rotational speed of the whisk about its shaft, rad s^{-1}
θ_r	angle created over time due to the revolution of the attachment shaft about bowl centre
θ_R	angle created over time due to the revolution of the attachment about its own axis
δ	gap between the whisk and wall, m
$\dot{\gamma}_w$	estimated peak shear rate experienced at the bowl wall, s^{-1}

Subscripts

k	Kenwood mixer
h	Hobart mixer

Table 1
Typical food processes and their associated shear regimes.[a]

Situation	Shear rate (s^{-1})							Example
	1		10		100		1000	
Extrusion		■	■	■	■	■		Pasta
Calendering			■	■				Dough sheeting
Pouring			■	■				Liquid foods
Mixing and Stirring			■	■	■	■		Food processing
Pipe flow		■	■	■	■	■		Dosing
Spreading (knife)[b]		■	■	■				Spreads

[b] Source: Stern and Cmolik (1976).
[a] Source: adapted from Steffe (1996).

employed in the food and pharmaceutical sectors. In the area of cake batters, although planetary mixers have been used for many years and it is known that the batter structure develops during extended mixing, published information on their operating characteristics is limited (Cauvain and Cyster, 1996).

Some studies of the flow patterns in planetary mixers have been reported, for a range of materials. Clifford et al. (2004) investigated liquid mixing in a simplified planetary mixer by visualisation of dye placed near the surface of a stirred vat of transparent liquid (golden syrup or glycerol). They observed complex, three dimensional flow patterns. Similarly complex patterns were observed for granular materials by Hiseman et al. (2002), who studied the flow of dry and wet (5–14 wt.% water) lactose powders in a planetary mixer using positron emission particle tracking (PEPT). They reported two flow regions, independent of agitator speed and level of fill: (i) a well-mixed central region characterised by rapid motion, and (ii) quasi-stagnant wall layers which were periodically disturbed by the passage of the mixer blade. The PEPT tracer particles transferred regularly between the two regions, implying that, averaged over time, all the material experienced similar shear histories. For both liquids and solids, it is clear that simulation of these shear histories would require extensive computational effort.

Linking material distribution and structure development during mixing is not straightforward for many food and pharmaceutical materials as these are frequently soft-solids (Coussot, 2005) whose structures and rheological behaviour can be stress or strain-rate dependent. Correlating the shear experienced during mixing with subsequent product properties has been attempted for granulation of pharmaceutical products (Schmidt and Kleinebudde, 1999; Visavarungroj and Remon, 1991) by comparing planetary mixers (representing low shear devices) to different designs of higher shear mixers. In such studies the shear regime was described qualitatively as 'low' and 'high', and quantitative information was only presented to differentiate the product properties. Knowledge of the range of shear rates experienced by a material during mixing is critical to understanding how its microstructure is developed during processing; to be meaningful, rheological data must be collected over the shear rate range appropriate for the problem in question (Steffe, 1996), which may vary widely in industrial processes. Given the complexity of planetary mixers, a reliable spatial distribution of shear rates and therefore shear history of even a Newtonian fluid is unlikely to be readily calculable, but knowledge of the range of shear rates – and particularly the maximum value – experienced during processing would be useful for comparing machines and methods.

To our knowledge the estimation of shear regimes during mixing has not been attempted previously for standard planetary mixers. Steffe (1996) reported (Table 1) the shear rate range 10^1–10^3 s^{-1} for mixing and stirring without detail of the calculation or geometries involved. Delaplace et al. (2005) studied a planetary device geometrically different to those considered here – a submerged, rotating impeller – and correlated the rheological properties over the shear range 0–500 s^{-1}, but again without justification.

The aim of this work is to characterise the maximum apparent shear rate experienced by a liquid in commonly used laboratory designs of planetary mixers. Particular attention was given to mixer speeds used in the preparation of cake batters. Extensional shear rates were not estimated.

2. Materials and methods

2.1. Equipment

Two planetary mixers with similar mixing capacities and fitted with balloon-whisk agitators were studied: a Kenwood KM250 (Kenwood UK Ltd., Havant) and a Hobart N50-110 (Hobart UK, London). Both whisk attachments were fabricated from stainless steel wire, around 2 mm in diameter, arranged in loops equidistantly positioned around the agitator axis to create an open structure (Fig. 1). The Hobart whisk was used as supplied, with 11 wire loops, and able to produce cakes with similar volume to industrially baked cakes. The Kenwood whisk was modified; the original tool was supplied with 5 wire loops, and 5 more were added inside the whisk, leaving the agitator profile unaffected. The addition of extra loops improved the volume of cakes produced from batters prepared with this mixer (data not shown), giving volumes comparable to those produced by the Hobart.

Table 2 summarises the settings and range of speeds available for each mixer. The rotational speed of a point on the whisk