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A systematic study of the residence time of flour in a vibrating apparatus used for thermal processing

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ABSTRACT

The dry heat treatment of flour is well established for the production of cake flour for high ratio cakes. This study investigates a new tubular apparatus in which flour is conveyed by vibrations through a helical pipe. Residence time distributions (RTDs) of flour were characterised for various processing conditions and the development of the residence time in extended operation was analysed.

A method was developed to accurately determine the RTDs, which could be approximated by normal distributions. The width of the distributions is a critical factor for the accuracy of a thermal process and was identified for different processing conditions. The distributions were narrow, with variations of ± 1% at most.

In some cases, the residence time increased over 3.5 h of machine run-time by 7.7%–13.9%. To explain this phenomenon, several hypotheses have been tested. The machine performance was constant with time and no influence of ambient temperature or humidity could be found. It was furthermore shown that changes in the bulk material passing through the apparatus were not the cause of the increase. However, electrostatic charging of the material was observed.

Two things led to a reduction in residence time: i) cleaning the pipe with a cleaning pig and water and ii) time, during which the machine is not running. It was suggested that a thin layer of particles inside the pipe in combination with electrostatics effects could be the reason for the residence time increase. Frequent cleaning can therefore allow relatively uniform behaviour and control of residence time.

Industrial relevance: This work investigates the potential application of a novel, vibrating device for the dry heat treatment of flour as a replacement for chlorination in the production of cake flour. Since chlorination was banned in the EU in the year 2000, there is an industrial interest for alternative treatments and equipment to produce flour for high ratio cakes.

1. Introduction

High ratio cake formulations are widespread in the UK in the production of sponges (e.g. Madeira cake), Angel cake, gateaux, slab cakes, or cupcakes (Hodge, 1975). Their sweet and moist characteristics achieved by a sugar to flour ratio of 1.0–1.4 are well appreciated by the market (Chesterton, Wilson, Sadd, & Moggridge, 2015; Guy & Pithawala, 1981; Magee & Neill, 2011). In comparison, cakes with lower or equal amounts of sugar and flour refer to low ratio cakes (Wilderjans, Luyts, Brijs, & Delcour, 2013). To achieve the desired attributes in high ratio cakes, it is required to use flour with a distinctive functionality to carry more water and sugar compared to flour used in low ratio cakes (Collyer, 1968). This was formerly accomplished by treating flour with chlorine gas (Collyer, 1968; Hodge, 1975).

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During the baking process of a high ratio cake, the viscosity of the batter increases due to starch gelatinisation and protein coagulation (Cook, 2002). The key element is that previously introduced bubbles by water vapour, heat expansion, and CO_2 expand and eventually burst due to increasing internal pressure transforming the viscous foam structure into a solid foam with uniform air cells distributed evenly throughout the cake (Cook, 2002; Meza et al., 2011). Untreated flour does not provide the necessary batter viscosity for the bubbles to rupture and the cake collapses when the temperature falls on removal from the oven (Cook, 2002). In contrast, chlorination increases the swelling capacity of the starch granules and the hydration capacity of gluten ensuring the mutual contact between starch granules after gelatinisation, increasing batter viscosity, allowing the cake structure to solidify in the final stages of baking and thus preventing the cake from collapsing (Collyer, 1968; Gough, Greenwood, & Whitehouse, 1977; Guy & Pithawala, 1981).

Whereas chlorination of flour is still used in the US, the process was banned in the EU in 2000 after concerns about health risks were raised

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(Catterall, 2000). Two general alternatives appeared to be other treatment processes or the modification of cake formulations (Gough et al., 1977).

In this context, Mangels in 1934 had discovered that the dry heat treatment of starch increased its rate of swelling in dilute sodium hydroxide solution (Hodge, 1975). This is the basis of the current heat treatment process of flour in industry, which generally involves 3 thermal steps followed by rehydration and milling (Chesterton et al., 2015). Specific details of flour heat treatments are not readily available in the public domain. In a first drying step, the flour is heated up and the moisture content is reduced, preferably below 4% in a stream of hot air (Chesterton et al., 2015; Neill, Al-Muhtaseb, & Magee, 2012). In a second heat treatment step, the flour is held at high temperatures by contact heating in rotated drums or heated conveyors (e.g. 120 °C–140 °C, 20–30 min) (Chesterton et al., 2015; Doe & Russo, 1970). After a cooling step to interrupt the heat treatment, the flour is rehydrated to a moisture content of e.g. 7%–12% (Chesterton et al., 2015; Neill et al., 2012). A final milling step is generally applied to break up agglomerates formed during rehydration (Chesterton et al., 2015).

As the dry heat treatment of flour is a physical modification, it is broadly accepted in public in contrast to chemical methods (Hodge, 1975; Thomasson, Miller, & Hoseney, 1995). Little is published about the alterations in flour generated by heat treatment, but the key effect of flour improvement appears to relate to the surface of the starch granules and its neighbouring layers (Guy & Pithawala, 1981; Magee & Neill, 2011). Two major effects of flour improvement by heat treatment were specified (Cook, 2002; Guy & Pithawala, 1981):

i) Improved swelling power of the starch granules and thereby increasing the batter viscosity
ii) Increased interaction between the starch and egg proteins, increasing the gel firmness for batters of treated flours.

In this study, a novel machine (Revtech, 2015) is presented that can potentially be used for the continuous heat treatment of flour. The core piece consists of a helical tube that is heated via resistive heating and that conveys the product from the bottom to the top of the spiral by vibrations. With the aim of designing a uniform and efficient process it is essential to investigate residence time distributions of the product passing through the machine as well as to examine the applied temperature profiles. The present work focuses on the residence time distributions depending on various processing conditions and their peculiarities with respect to the dynamics of the system.

2. Materials and methods

2.1. Material

Commercially available high ratio flour (protein content 8.6%) with the particle size distribution shown in Fig. 1 (calculated from triplicates) was used for the experiments. Bulk density and tap density were measured to be 0.51 ± 0.003 g/ml and 0.81 ± 0.01 g/ml.

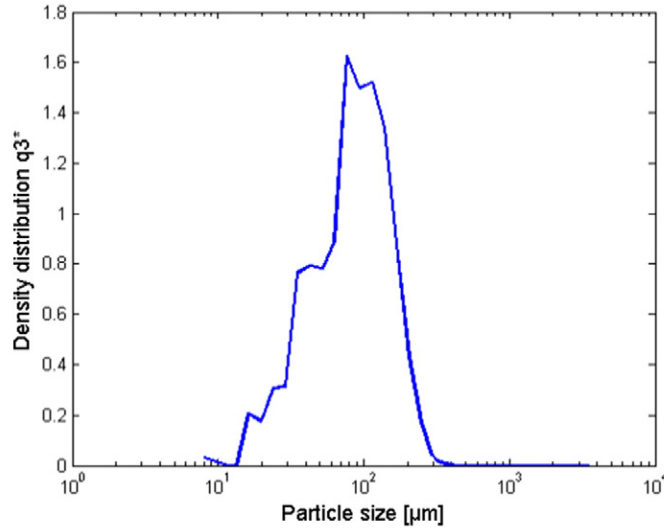

Fig. 1. Particle size distribution of high ratio flour.

2.2. Equipment

The equipment used for the experiments is a continuous, thermal processing unit manufactured by Revtech process systems (Loriol-sur-Drome, France). It consists of three major parts, a hopper, a heating spiral, and a cooling spiral. In this study only the hopper and the heating spiral were used for simplicity. As shown in Fig. 2, particles are conveyed by a screw feeder (B) from the hopper (A) into the spiral. It is a helical, steel pipe (C) with an internal diameter of 84.5 mm, a slope of 2.83° to the horizontal, and a length of approximately 34.4 m. It is possible both to heat the pipe by resistive heating and to inject steam. The screw speed controls the overall particle flow, whilst the behaviour in the tubing is controlled by the vibrations of the motors. Two off-balance motors (D) are attached on opposite sides of the spiral and at an adjustable angle with the horizontal. They create vibrations of different amplitudes and frequencies. The vibrations can be controlled by changing:

- *Motor angle*. The movement of the motor is perpendicular to the motor axis. Adjustment of the motor angle β affects the velocity components of the motors in horizontal and vertical direction. This is shown in Fig. 3 and the components are defined as Eqs. (1) and (2). With increasing angle β, which ranges between 0° and 90° ($\alpha = 90° - \beta$), the horizontal velocity component increases, whereas the vertical one decreases.

$$v_x = v \cdot cos(\alpha) \quad (1)$$

$$v_y = v \cdot sin(\alpha) \quad (2)$$

- *Motor speed*. This controls the vibrational frequency of the oscillations and can be adjusted between 600 rpm (10 Hz) and 740 rpm (12.3 Hz).

The vibrations cause particles to move from the bottom to the top of the spiral. The product leaves the helical pipe via a flexible plastic tube that is connected to the top and it is collected in a plastic container.

For the experiments, the hopper of the machine was typically filled with approximately 100 kg of flour, which allowed for a 1 h experiment (100 kg/h). The flour was recirculated and the fraction lost (ca. 5%) through sample taking was topped up prior the next experiment (recirculation method).

A dry and a wet cleaning method can be applied to the spiral. A cleaning pig is used in both cases to push the remaining product out of the pipe. Compressed air is used in one case and water in the other to drive the cleaning pig through the pipe. In one case the hand dishwashing liquid Suma Star plus D1 plus (JohnsonDiversey, Inc.) was added to clean the pipe.

2.3. Determination of residence times

2.3.1. Residence time distributions

The residence time distributions of flour in the vibrating machine were measured at ambient temperature. Twenty-five grams of burnt flour (15 min at 250 °C in a convection oven) was used as a marker that was introduced instantaneously to a constant flour flow of 100 kg/h (insertion point E in Fig. 2). The time was taken with a